You and the Universe

An opinion

by PROFESSOR ERWIN SCHRÖDINGER

on this book

"I was surprised by the fantastic richness of your ideas, the ever-changing costumes by which you effectively and permanently keep monotony . . . at arm's length."

PAUL KARLSON

You and the Universe

Modern Physics for Everybody

TRANSLATED BY
BERNARD MIALL

With 165 Sketches
by W. PETERSEN
and 8 Plates

SPECIAL EDITION
for the
SCIENTIFIC BOOK CLUB
121 Charing Cross Road
London W.C. 2

LONDON
GEORGE ALLEN & UNWIN LTD

THIS EDITION PUBLISHED IN 1938

PRINTED IN GREAT BRITAIN BY
UNWIN BROTHERS LTD., WOKING

PREFACE

"We have found a strange footprint on the shores of the unknown. We have devised profound theories, one after another, to account for its origin. At last, we have succeeded in reconstructing the creature that made the footprint. And lo! it is our own."

A. S. EDDINGTON

WE physicists have always endeavoured to obtain a clear image of the environing Universe; that, after all, is what we are for, and we have regarded our problem as difficult, but solvable. We have seen our goal in the distance—the Universe itself—and towards it we have eagerly fought our way, now rapidly and directly, now along bypaths and through obstructions; we reinforced our eyes with spectacles and telescopes—and we thought we could see a clear, sunny landscape, with trees, houses, and machinery. Now we stand close before it, and with a shudder we realize that all the imagined clearness has vanished. We are confronted by vague, colourless, drifting wreaths of mist, which melt away as we approach them more closely. Indeed, we could almost fear that the whole animated landscape was a mere delusion: so many smears on our lenses. This is what is known as the revolution of physics; and it is of this revolution that we shall speak in this book.

But one can hardly speak of this process of dissolution before one has described the image that has dissolved. Among the physicists the layman is like a man who comes into the theatre only after the first interval. A door opens, and on the stage appears a singular figure—let us call it the Positive Electron—at the very sight of whom there is an outburst of uncontrollable laughter; the physicists in the audience are beside themselves with delight. The layman stares and wonders. He sees no reason for all this merriment—he knows nothing of the part which the Positive Electron is playing. In a word: he has not seen the first act.

And it is just the first act that is important; the second is more a private performance for connoisseurs. So I have felt that I ought to begin with an account of the opening act—of

ordinary physics, which outside the physical laboratories still governs, as it always will, our technical activities and our lives; that I ought to explain the connection between electricity and light; what an atom is; how wireless telegraphy is possible, and how "radio" operates—in short, to jot down the outlines of the modern Universe. Of course, we must not forget the second act of the drama—the revolution in modern physics.

This I have described without mathematics, and as simply as possible—just as I described it to my friend Peter, who has no head for physics. In the subjects which we shall consider so much solemnity and dignity are inherent that I think we can afford to dispense with these qualities in expounding them. "Physics," says Peter, "is a subject I have never been able to understand!" But I cannot think that the matter should be left there. They tell me that many Central African negroes are exceptionally good chauffeurs, though they understand very little about the mechanism of a car. Our modern technicians and physicists are often inclined to treat the layman as a sort of negro, as though none but themselves had any right to think about the internal processes of the Universe as we conceive it today—or even of a radio receiver. This tendency should be opposed. We have a right at least to some degree of initiation, and in order to obtain it I do not think one needs more than a little good will. We do not want to wait behind locked doors for the next surprise.

PAUL KARLSON

BERLIN
November 1934

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PART ONE
MATTER

I. THE BRICKS OF THE UNIVERSE

THERE was a rumpus at the whist-drive in the "George and Dragon." For the tenth time Farmer Giles, who is fond of "dictionary words," had caught his neighbour trying to overlook his hand, and at last he lost all patience. "We might just as well play with our cards on the table!" he stormed. "Shameless behaviour, I call it! There's only one thing to be done

with an undesirable element—and that is, kick him out!" It was an outburst of elementary violence, but it failed in its purpose. The other players were no longer in a condition to appreciate the moral issue. As for the culprit, he defended himself stoutly, though his tongue was a little heavy. "I'm not an undesirable element!" he protested. "Not undesirable, and what's more, I'm not an element!"—"I tell you you are, and a nasty one too!"

The words buzzed to and fro in the low, smoke-filled room. "Fire, Water, Earth, Air!" sang someone in the corner, before blissfully pulling at his pint tankard. "But the elements don't get on together!" A shrill voice rose above the din: "Come, gentlemen, come, don't you know what an element is? An element . . .." But the rest of his speech was drowned in the general uproar. The "George and Dragon" will never learn what an element is.

Fire, Water, Earth, Air—these were the elements of the ancients; the basic substances from which all other substances

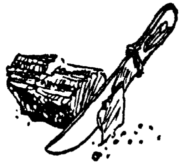
arose. We know today that this division, which originated in philosophical, not physical and chemical, considerations, is untenable—that these four "elements" are not elements at all as we understand the word today. An element is a *basic* substance, which cannot, by any chemical process, be farther analysed. An example: In the woods a tall, slender spruce-tree is growing. It is felled and cut into planks, and of these a table is made; or it is sent to a pulp-mill, and finally becomes newsprint. No one recognizes the spruce-tree again in the stained and polished table or the morning paper; yet it is still the same wood. But if the chemist, in his laboratory, analyses the wood, attacking it with his acids, his crucibles, and his reagents, he will find that it is built up out of three essential components: carbon—and coal, we know, consists mainly of carbon—oxygen, the gas which is so indispensable to life—and hydrogen, the lightest gas we know, the gas that is used to fill our balloons and dirigibles. And even the most skilful chemist cannot analyse these three substances—carbon, oxygen, and hydrogen—any farther. They are and remain *simple* substances; that is, they are not compounded of other substances; they are basic substances, *elements.*

The four elements of the ancients have not withstood this "acid test." Fire, as we know today, is not a substance at all, but only vibration and smoke. Earth is material enough—a mixture of thousands of substances and a great number of elements. Air is a mixture of different gases—mainly oxygen and nitrogen. And lastly, water is a compound of two well-known elements—oxygen and hydrogen. The classification of the ancients was very nice and poetical, but we cannot accept it today.

Elements, Molecules, Atoms

The chemists of the nineteenth century found that there were ninety-two elements. Ninety-two; a very large number, compared with the original four! But our modern classification has the best of it, for these are really *elements,* chemically indivisible. *Chemically* indivisible—but that is only one aspect of the

matter. By other means, of course, an element can be farther divided. I can take a lump of coal, for example, and break it into pieces; and each of these pieces I can break into smaller pieces. This is a crude, mechanical division. Each little fragment of coal remains just as *simple*, just as chemically elementary as before. But this breaking into fragments leads us to a new question: If anyone were to take a sharp knife, and put on his spectacles, and cut little chips from this coal, tiny little chips, and then cut these in two, and cut them again and again—would there come a time when he could divide them no farther? Even with instruments of the most infinite delicacy?



Democritus said "Yes"; and we physicists are of the same opinion today.

It is the fashion to begin with Democritus if one touches on this problem: Democritus, the old Greek philosopher and materialist, who asserted that *all things in the Universe consisted of ultimate, minute, indivisible parts*—the *Atoms*, so called because they were *a-tomos*, indivisible. He imagined these "building-stones of the universe" as minute rigid particles, rather like so many tiny "Anchor" bricks. At the same time, there were different sorts of atoms—thick, thin, round, triangular. Democritus denied the existence of soul or spirit. He believed, as many investigators who followed him believed, that the hypothesis of "spirit" was unnecessary. For him the human soul was a subtle, fiery *substance*, consisting of the lightest spherical atoms. And he sought to explain the sensory perceptions as the crudely materialistic influences of the outer world—as the reciprocal effect of the atoms—as the impacts of atoms which entered the body through the sensory organs.

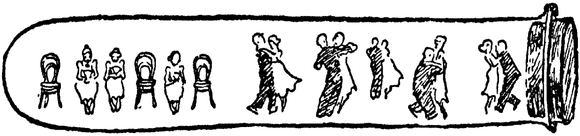
Democritus was a philosopher. The physicists were interested in another aspect of the problem. In 1802 Dalton, an English scientist, as a result of his chemical investigations, restated the *atomic theory*.

Most of us, in our youth, knew the delights of the dancing-lesson. A couple of dozen girls and as many boys, all on their

best behaviour, sat on chairs against the longer sides of the brightly lit hall. The girls whispered and giggled; the boys nervously fingered their ties, or negligently, with experienced eyes, considered the opposing front.

And at the first thundering chords on the piano these lords of creation rose to their feet, crossed the polished floor with stiff, uncertain steps, and made their bow; and the couples glided off—one, two, three, one, two, three. . . . That was when all went well. But if one or more of the boys failed to turn up, then one or more of the girls had to remain sitting by the wall—so many melancholy wallflowers!

It was reserved for Dalton to discover such "wallflowers" in chemistry and physics. His experiment is so simple in its main features that it seems obvious today. You all know



spirits of salts, a strong corrosive fluid. It is a solution of a particular gas—chloride of hydrogen—in water. This gas can be split into the two elements—again, two gases—chlorine and hydrogen. Dalton tried to reverse the process; he wanted to build up chloride of hydrogen from its two components. He accordingly introduced a measure of hydrogen and a measure of chlorine into a large spherical vessel—where they united with an explosive bang to form two measures of hydrogen chloride. If he took two measures of each gas the final result was four measures of hydrogen chloride. But if he mixed two measures of hydrogen with only one measure of chlorine he found that a "wallflower" was left over; he got two measures of hydrogen chloride and the other measure of hydrogen was left without a partner! Bewildered and lonely, it wandered about the container. It was "left over!"

"That is just what I expected," thought Dalton, rubbing his hands; for he had studied his Democritus to some purpose. "Here are hydrogen atoms and chlorine atoms—units, not further divisible. If I bring them together each hydrogen atom

seeks out an atom of chlorine, makes its bow, and begins, closely embraced, to waltz away through time. In other words, they are wedded. But a hydrogen atom that cannot find a chlorine atom, because all the chlorine atoms have all gone off with their partners—well, it is left in the lurch, a wallflower, an eternal spinster or bachelor. "I shall call this married pair a molecule," Dalton resolved. (Or if he didn't do so, his successors did.) Two atoms together form a molecule; the molecules are the smallest bricks of hydrogen chloride.

As you see, the atomic theory of Democritus enables us immediately to explain Dalton's experiment; but without this theory the experiment would be wholly inexplicable. We can no longer doubt the result of our tedious coal-carving. The man with the impossibly sharp knife would come to a full stop at last; he would discover the bricks of the coal—he would obtain the molecules in "pure culture," as the bacteriologists say; just as anyone who attacked a big house with a pickaxe would finally obtain a great heap of bricks as the result of his efforts. Well, every substance on earth, or in the heavens, or in the waters that cover the earth, consists of molecules, of wedded atoms, micro-marriages. Even hydrogen consists of molecules; each molecule being built up out of two atoms of hydrogen. But the atoms are by no means always as strictly monogamous as they are in chloride of hydrogen. There are triangular marriages—and they are very frequent. Water is an example of such. One atom of oxygen and two atoms of hydrogen have joined hands, and go dancing united through life. If you dip the wires leading from the + and − poles of an accumulator or secondary battery into a glass of water you will see tiny bubbles of gas rising from the wires. The electric current passing through the water is dividing it into its elements. On the wire leading from the positive terminal twice as much gas is formed as on that leading from the negative, and we recognize that this is a case of a triangular marriage, so that for every husband (or atom of oxygen) two innocently divorced wives (atoms of hydrogen) make their appearance. But the case of water is one of the simplest. There are such things as whole societies of atoms which have welded themselves into a molecule; a molecule of grape-sugar, for example,

contains twenty-four associate atoms. And among the albumens of the human body we find giant molecules which consist of hundreds and even thousands of molecules; micro-societies, almost visible in the microscope. But there are also a few inveterate solitaries—melancholy bachelors, who are always found alone. To these belong the metallic gases, and the curious "inert" or "noble gases" (helium, the non-inflammable gas which can be used to fill balloons; and neon, which burns in a vacuum-tube with a magnificent warm red glow, yet remains cold and chaste; argon, etc.). They prefer "splendid isolation"; they are known as *monatomic*; every molecule consists of only a single atom, so that in their case there is no longer any difference between atom and molecule.

The logical order is clear: Every substance on earth consists of molecules, of tiny building-stones or bricks. In the overwhelming majority—with the exception of the "noble" gases and the metallic vapours—the molecules are built up out of a larger or smaller number of atoms. The molecules of a chemical *element* consist of mutually similar, indistinguishable atoms. When *different* atoms come together we have a *compound* of elements. Chemistry knows perhaps two millions of such compounds. They are all built up out of ninety-two elements—ninety-two, but of these only twenty at most play an essential part in the structure of the Universe. Nature seems to have created the rest in a spirit of scientific systematics.

Structure

There are two ways of taking a watch to pieces: the way of the watchmaker and the way of the inquisitive child, who goes to work without undue consideration, in order "to see what's inside." In the end each of them has before him, as the result of his efforts, a heap of cogwheels, screws, and little pinions. The child, of course, knows only that all these were put together somehow, and "went"; but the watchmaker understands the meaning of them all; he knows how they were put together, and in which position each little cogwheel or pinion must be placed in order to do its work.

The imaginary man with the knife, cutting the lump of coal

into fragments, was like the child; as the result of his work he had an untidy heap of molecules before him. He knew what the world was made of, "what was inside"—just molecules. But sooner or later every science outgrows this childish stage, and inquires into the laws of construction.

So the time came when chemistry began to inquire *how* the atoms are arranged in molecules. It discovered, for example, the chain-molecule of many organic compounds, in which atom is joined to atom in a long, thin chain, and this chain may attain a quite astonishing length—reckoning, of course, in the molecular order of magnitude; or the three-dimensional, "pyramidal model" of the carbon compounds, which we owe to the great chemist van't Hoff, and in which the atoms are situated at the angles and at the central point of a pyramid.

We may also inquire into the structure of the next unit—into the mutual connections of the molecules and their arrangement in matter. But here we shall have to distinguish between the three "aggregate states" of matter—between its three forms: gaseous, fluid, and solid.

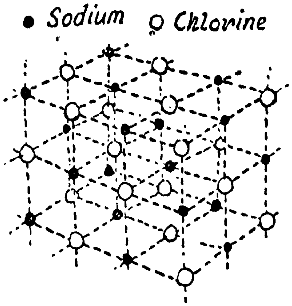
Gases.—Here, if we were filling up an official document, we should have to write, under the heading of "structure": "None." In gases there is no sort of connection between the molecules. A sheer anarchic individualism prevails. Like the midges in a swarm, the molecules of gas go whizzing wildly past one another. A gas is a lawless chaos: a terrifying image to the conventional and form-loving mind.

Fluids.—Here the gas has condensed. You know how the water vapour in the atmosphere forms clouds—condensing into little particles of mist, which combine to form big raindrops. Now the molecules lie close together, influencing one another by means of electrical forces. But these forces are still so small that no permanent formation results. External forces—pressure, gravity—can alter the shape of the fluid almost without resistance. Water readily moves aside if I thrust a pencil into it, or my hand. It is true that the molecules lie close together; this we can deduce from the fact that fluids are practically incompressible; that in a hydraulic jack, for example, they can be made to support enormous burdens. A fluid is like a closely packed crowd of human beings, or a dish full of peas,

in which each individual is still free to push against his neighbours. But at the surface single molecules keep on tearing themselves loose and escaping into the open; that is, the fluid is *evaporating.*

Solids.—Here at last the unruly spirits are compelled to obey a uniform law: each must perforce take its place, in a harmonious, regular arrangement. *Form* crystallizes out.

We will take ordinary rock-salt as the simplest representative of the genus. In the language of chemistry, this salt is sodium (natrium) chloride—a combination of the gas, chlorine and the metal, sodium; and see what comes of such a combination!



Strangely enough, in rock-salt the individual atoms are no longer united to form molecules. We cannot speak of a molecule of salt. The atoms lie side by side, an atom of chlorine being always next to an atom of sodium. They occur at regular intervals, arranged in the form of a cube. The whole system is maintained in equilibrium only by its reciprocal tensions, each atom being free to oscillate slightly about its place. Such a trellis-work of atoms we call a *crystal.*

In the crystal of rock-salt we find the simplest form of trellis-work. There are many other forms, and some of them are extremely complicated. But one thing is common to them all: the "bricks" are held fast in a regular trellis-work formation, and are able to make only slight oscillations about their appointed place. If we heat the crystal the oscillations grow more and more energetic, and at last—at a perfectly definite temperature—the crystal scaffolding collapses, and the "bricks" are free! The crystal has melted!

Every solid substance is symmetrically built in this fashion. But this form of structure is not as a general thing so consistently and uniformly followed as in the substances which we commonly call crystals—such as quartz and diamond, for

example. In the majority of substances—metals, rocks, etc.—the structure is constantly interrupted and begun over again, so that small separate regions, known as "crystallites," are all jumbled up together. In this way the crystalline structure vanishes, and appears again only if we subject the substance to a strict scientific examination.

The glasses alone form an inglorious exception. In glass there is no trace of a crystalline structure. Glass has no fixed and definite melting-point; when heated it slowly softens, and at last becomes fluid. So science shrugs her shoulders, and says contemptuously: Glass is not a solid substance at all—it is a fluid!

The Police Archives of the Chemist

There are ninety-two elements—ninety-two basic molecules—or, what is more important, ninety-two sorts of atoms, with which the millions of compounds found in the universe are built up. Democritus would have cause for amazement today!

Ninety-two—it seems little beside a few millions! Yet there is something unsatisfactory in the thought that these ninety-two elements should stand so calmly side by side. Why are there not more, or fewer? Why aren't there ninety-six, or only two? And is there not perhaps a still closer relation between some of these many different atoms?

In every police headquarters of the great cities there is a big room in which plain varnished cabinets line the walls. They are really big chests of drawers, and every drawer is marked with letters and names; beginning, for example, with A—Ackersly and ending with Yates—Zyskov. This is the criminal file. Every citizen, male or female, who has at any time diverged from public opinion in his or her interpretation of the law, has his place here on a special sheet of the records. Three excellent photographs adorn the top of the sheet; then come the personal data—height, colour of hair, etc., and finally the finger-prints. And when anyone gets up to mischief of any sort anywhere, his personal data are compared with those contained in this card index, and if they are already

PERIODIC SYSTEM OF THE

1 H 1·0078		Group VIII 0	I *a* *b*	II *a* *b*
Valency to H		0 Various	1	2
to O		0 Various	1	2
Period I	Series 1	2 He 4·00	3 Li 6·94	4 Be 9·02
Period II	Series 2	10 Ne 20·18	11 Na 22·99	12 Mg 24·32
Period III	Series 3	18 Ar 39·94	19 K 39·10	20 Ca 40·08
	Series 4	26 Fe 27 Co 28 Ni 55·84 58·94 58·69	29 Cu 63·57	30 Zn 65·38
Period IV	Series 5	36 Kr 83·7	37 Rb 85·44	38 Sr 87·63
	Series 6	44 Ru 45 Rb 46 Pd 101·7 102·1 106·7	47 Ag 107·88	48 Cd 112·41
Period V	Series 7	54 Xe 131·3	55 Cs 132·81	56 Ba 137·36
	Series 8	76 Os 77 Ir 78 Pt 190·8 193·1 195·23	79 Au 197·2	80 Hg 200·61
Period VI	Series 9	86 Rn (Ra Em) 222	87—*	88 Ra 225·97

* 57 La, 138·9; 58 Ce, 140·13; 59 Pr, 140·92; 60 Nd, 144·27; 61 Il (?); 62 Hu, 163·5; 68 Er, 167·64; 69 Tm, 169·4; 70 Yb, 173·5; 71 Lu, 175·0.

† Two elements not yet discovered: 85 (ekaiodine) and 87 (ekacaesium)

CHEMICAL ELEMENTS (1932)

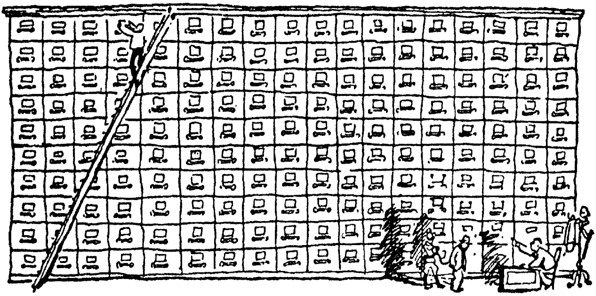
III		IV		V		VI		VII	
a	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
3		4		3		2		1	
3		4		5		6		7	
5 B 10·82			6 C 12·00		7 N 14·008		8 O 16·00		9 F 19·00
13 Al 26·97			14 Si 28·06		15 P 31·02		16 S 32·06		17 Cl 35·46
21 Sc 45·10		22 Ti 47·90		23 V 50·95		24 Cr 52·01		25 Mn 54·93	
	31 Ga 69·72		32 Ge 72·60		33 As 74·93		34 Se 79·2		35 Br 79·92
39 Y 88·93		40 Zr 91·22		41 Cb 93·3		42 Mo 96·0		43 Ma ?	
	49 In 114·8		50 Sn 118·7		51 Sb 121·76		52 Te 127·5		53 I 126·93
57–71* Rare earths		72 He 178·6		73 Ta 181·4		74 W 184·0		75 Re 186·31	
	81 Tl 204·39		82 Pb 206·22		83 Bi 209·0		84 Po 210·5	85—†	
89 Ac *Circa* 227		90 Th 231·12		91 Pa 235		92 U 238·14			

Sm, 150·43; 63 Eu, 152·0; 64 Gd, 157·3; 65 Tb, 159·2; 66 Dy, 162·46; 67

probably radio-active and difficult to find.

there the man is identified. And then, if this is a case of a notorious "recidivist," he does a few years more "time."

Chemistry, too, has long possessed such an index. It is called The Periodic System of the Elements. All the ninety-two elements of this Earth of ours are there neatly classified; and the chemist enjoys this great advantage over the criminal police—that there seem to be no further, undesired elements over and above these ninety-two. According to their weight, their colour, their chemical and general behaviour, they are entered in a great table. The idea of such a table was con-



ceived by the German, Lothar Meyer, and the Russian, Dimitri Mendeleieff, both of whom, in 1869, simultaneously set to work on this general classification.

The elements were at first arranged in order of *weight*. At the head of their table, then, they placed hydrogen, the lightest substance we know—and according to modern views the lightest there possibly can be. Then came the "noble" gas helium; followed by carbon, nitrogen, oxygen, etc. The heaviest element closed the series: uranium, a metal found in Bohemian pitchblende. Now in this simple classification, in making which the chemist arranged the elements in order of weight—just as a child might thread beads on a string in order of their size—certain surprisingly systematic features become apparent. It is as though, on threading a number of beads in order of size, we found, for example, that every eighth bead was red, and the next always green, followed by a black, a yellow, a blue, a white, an orange, and a lilac bead—and then again by

a red bead, a green one, and so forth. Anyone who considered such a string of beads would inevitably come to the conclusion that it had been consciously and systematically arranged in this sequence of colours. And yet the only rule which the child followed was the rule that each bead must be bigger than the last.

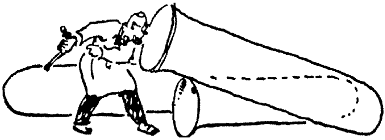
The Fortunate Gaps

Such a systematic arrangement is wonderful enough in itself. But its exactitude, in the historical advance of science, proved to be much more astonishing. When Mendeleieff first examined this string of elementary beads he was thoroughly startled, and to his great annoyance he had to admit that after two complete series—as it might be, red, green, black, yellow, etc.—the third series was red, black, yellow, etc. "There's a bead missing here," one would have told a child—anyone would have said it. And Mendeleieff too, the great chemist, was so convinced of the correctness of his system that he cried, reproachfully: "There's an element missing here!" The idea that his system might be incorrect simply did not occur to him; he coolly requested the practical chemists to look for this absent element.

Now the chemists of that day had already thoroughly searched the whole earth for new elements. But Mendeleieff was able to give their search a new and methodical basis. "Don't simply look for the bead," he cried. "Look for a *green* bead, exactly one inch in diameter!" But he knew much more than that about the thing that had to be looked for. He was able (to go back to our image of the file of criminal records) to issue a warrant for its arrest, with full personal data: Wanted, Element No. 32—height, individual characteristics, probable place of residence, etc. All was then comparatively plain sailing. The experienced practical chemists very soon found the fugitive, and reduced it to a chemically pure state.

And so, in quick succession, the so-called "national"

elements were brought to light—germanium, gallium, skandium, so called in honour of the nationality of the discoverer: German, French, Scandinavian. The gaps in the system were being closed. A few remained even until quite recently. But their absence no longer imperilled the firmly based *periodic system.* The absent elements—so the chemists were forced to conclude—existed everywhere in such small quantities, were



so finely divided, that they had hitherto succeeded in evading chemical demonstration; it was almost impossible that they did not exist, but they could not be detected. The concentration of such a substance must be almost inconceivably small.

One of the finest examples, in recent times, of the search for such a substance is the story of Element 75, or the hunt for *rhenium.* In 1927 almost everything was known about a certain missing element. No. 75 in the periodic system. But as yet no one had been able to lay hands on the element itself—even with the Röntgen-rays, by means of which almost infinitely small quantities of matter can be detected; but here the method failed. So Walter Noddak and Ida Tacke devised a magnificent experiment: Investigation of the unknown, or chemistry in the void! As yet—they said—it has not been possible to demonstrate the presence of the unknown element in the material at our disposal. But for once we will proceed *as though it were there.* . . . We know well enough what the qualities of X 75 must be—the periodic system tells us that. And we will proceed as though we had already discovered it, and do our best to obtain it in the pure state. We will concentrate X 75 in our experimental solutions before we have discovered it! —They were like two hunters who had somehow acquired the conviction that there must be hares in a certain covert; but perhaps only two or three, too few to be discovered in the great wood. So they began, systematically, to strew food about,

and to exterminate the foxes and ravens and carrion crows and such-like creatures of prey. And lo, after a few years the hares were so numerous that first one was seen, and then another, and at last the wood was swarming with hares! This was very much how the two investigators proceeded—and after innumerable washings and precipitations and distillations they at last obtained on their X-ray film the first black streak: X 75, the unknown element rhenium, was discovered!

Incidentally, it may be remarked that today these two research-workers publish their results over the signatures of W. and I. Noddak. So powerful are the combining forces of chemistry!

Personal Data: Unreliable

We must have order, thought Inspector Briggs, as he neatly arranged his pencils until they were exactly parallel, and stacked his papers together—the warrant for the arrest of the habitual street-robber and crib-cracker Nobby Hawkins on the top—threw a contented glance at the tidy desk, and an angry one at the cunning, unshaven features of Hawkins, and left the room.—This was in the evening. Next morning, when Briggs entered the room, and sat himself down to work, after a complacent glance at his tidy desk, he broke off in his cheerful whistling and rose angrily to his feet. Instead of the crafty, unshaven Hawkins the inoffensive, rather imbecile, and almost hairless countenance of the bigamist Higginson was gazing up at him. "A silly sort of joke!" he grumbled, stumping across the room to his file of criminal records,

in order to exchange the bigamist's identification-card for the right one. But Hawkins was not in his place, and as he angrily pulled out the second drawer, there too, ingenuous as ever, a Higginson smiled up at him. There was no help for it—the vicious, unshaven Hawkins had transformed himself overnight into the bigamist. Inspector Briggs raved and stormed. How could one make out a proper warrant if the personal details

changed of themselves during the night?—Sad to relate, in 1896 the chemists were in just such a quandary as Inspector Briggs.

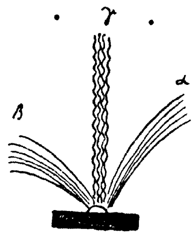


To begin with the problem seemed simple enough. Becquerel, a French chemist, who had been experimenting with uranium, left a sample of ore lying all night on a photographic dry plate. The plate was enclosed in a light-tight box; nevertheless, on developing it Becquerel found a black spot where the sample of ore had been resting above it. Some unknown ray of light must have affected the plate—a ray which could have come only from the uranium, and which was able to penetrate the thick cardboard of the plate-box. Only the year before Röntgen had made his wonderful discovery. Had Becquerel discovered a new sort of Röntgen rays?—The curious phenomenon was diligently investigated. Marie and Pierre Curie discovered the explanation. Amazed and dazzled, the physicists found themselves on the threshold of a new and unknown world.

Radium was the name which Mme Curie gave to the element which emitted the mysterious Becquerel-rays. Radium—a heavy metal, nearly related to the known metal, barium—filled one of the gaps in the Periodic System. Place No. 88 was waiting for it; and its weight was 226.

The radium content of the uranium ore found in the Joachimsthal pitchblende is almost inconceivably small. Ten tons of pitchblende yielded at the very most a gramme—15 grains—of radium. And the cost of obtaining a gramme of radium was £8,000, while its market value was almost three times as much. It was a masterpiece of analytical chemistry.

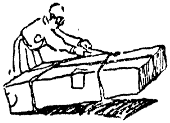
Well—now they had discovered and obtained the radium, and were able to investigate the mysterious rays more closely. It was shown that three different sorts of rays could be distinguished: 1. *Alpha-rays*: minute, heavy, positively charged particles which are shot out of the radium with terrific force. These were held to be responsible for the blackening of the photographic plate. 2. *Beta-rays*, very light and negatively electric—and it was soon discovered that the β-rays are simply *electrons*—charges of negative electricity, moving at a tremendous speed. The velocity of the β-rays is almost as great as the velocity of light—186,000 miles per second, which is the greatest velocity in the Universe. 3. *Gamma-rays*—which proved to be very powerful, hard Röntgen-rays; a thousand times more penetrating than the most powerful rays artificially produced.



Have you ever seen armour-plate tested by artillery? If so, you know that after a few shots the heavy steel plate may grow almost red-hot. The heavy projectile is suddenly checked on impact and penetration, and its tremendous energy, its momentum, is transformed into heat, the heat of friction. The α-rays, those heavy, swiftly moving particles, are likewise checked by the bodies upon which they strike, for they lose velocity even in passing through a few inches of air. But their energy cannot disappear—and here, too, it is transformed into heat, the heat of impact and friction. The α-particles which 5 lb. of radium are constantly discharging would produce enough heat in an hour to boil a pint of water. Consequently every specimen of radium is always a few degrees warmer than its environment, and will always remain so.

Always? To all eternity? Day after day, year after year, the radium emitted its mysterious rays, pouring its energies out into the world. Where did they come from? Did the radium make its rays out of nothing? Was the law of energy violated here? This the physicists could not believe—and at last they hit on the explanation; but it was, if possible, even more

inconceivable than the fact itself. An English scientist, Rutherford, discovered the solution; Radium is an element which is really not an element at all. If 1,000 grammes of radium were shut up in a box of some impenetrable material, then a year later this box would contain only 999 grammes of radium—but it would also contain a number of other elements, whose total weight would be 1 gramme. Radium, the element, the supposedly indivisible basic substance, slowly but steadily changes, in the course of time, into another element.



The Radium-Atom Disintegrates

Quite automatically, immune to the influence of any human agency, in accordance with obscure and inexorable laws, the radium-atom disintegrates. It shoots out its α-rays, and these α-rays, these tiny, mysteriously heavy particles, are really nothing more or less than the long-known gas *helium*—for every α-particle is a helium-atom. The residue is not radium, but *radium-emanation*, a new element. The old dream of the alchemists has thus become sober reality in the laboratories of the twentieth century. The elements, the basic materials of all substance, are not final and absolute entities!

The disintegration of the elements! It is not easy to describe the excitement that seized upon the scientific world. The elements, the foundation of all chemistry, were not ultimate? The Periodic System, that marvellous discovery of Mendeleieff's, whose theory had been confirmed a thousand times over—was a thing invalid and unproven, a mere matter of blind chance? The scientists must have felt as if the world was coming to an end. A whole scientific system was tottering. If not even the elements were permanent, what was there anywhere to which one could hold fast? And the deeper the research-workers delved into the miraculous region of radio-activity, the greater was their astonishment.

For radium was not the only element to surprise them. Others were discovered—mysterious, radio-active elements

which disintegrate and transmute themselves into other radio-active elements. Even the tempo of their disintegration can be determined. The time which must elapse before half the substance has disintegrated is known as the "half-value period"; but all the radio-active elements have not the same half-value period. There are mayfly elements among them, elements whose life is only a fraction of a second, which disintegrate immediately, like the so-called Radium C′, whose half-value period is one millionth of a second; but there is no doubt whatever that they are real chemical elements. And there are others which last for thousands and millions of years—thorium has a half-value period of 20 thousand million years!—but which emit their radiations, and slowly, very slowly transmute themselves; even these, though they do not, like the others, vanish with rocket-like celerity, are continually and inevitably disintegrating. So radium does not emit its rays to all eternity. The number of the radium-atoms in Rutherford's containers is always diminishing; of 1,000 grammes only 500 would remain after the lapse of 1,580 years. After the lapse of another 1,580 years—that is, in the year 5096 —a quarter of the original quantity would still be left; the box would still contain 250 grammes of radium. But one day, in the dim future, the last atom of radium will have been overtaken by its fate. One final α-ray, and the radium will have finally dissolved.

In some fearful and wonderful way dead matter seemed to have come to life. What we thought eternal and indestructible was decaying, and no human power could affect the process. Irresistibly the radium-elements were emitting their radiations. No earthly agency could alter their half-value period. Man could do nothing but resign himself to observing the process, powerless to stay it. What were the higher laws which these singular substances obeyed? Did such laws even exist?

Lord Rutherford Builds a Universe: A Fairy-Tale

"You see," said my host, "there was then one question only which had to be asked: What is an atom?" We were sitting over the fire in the scientist's study. A thin thread of smoke rose from his pipe as he gazed into the flames. "People were beginning to suspect, even then, that the atoms themselves are built up, and consequently have no right to the name of atom. But I would rather tell you a story—a story about the creation of the world.

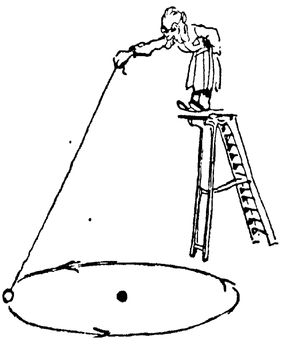
"Really, the thing was quite simple. Lord Rutherford, in his experiments, had detected the porous structure of matter; that is, he had realized that fundamentally the world was an absolute fraud. He had found Nature out. He had discovered that matter is not really firmly compacted. It only seems so to us, because the atoms of which a substance is composed—for example, the wood of my desk—are held in stable equilibrium by reciprocal electrical forces. In reality there are far more holes than solid portions. Rutherford thought he knew what the real fundamental 'brick' of matter must be; simply the electron; a very light, very small particle of negative electricity. And secondly, the so-called proton: a positively charged particle, 2,000 times heavier than the electron. Both carry an equal charge of electricity, but in the one case the charge is negative, in the other positive. We shall touch on this again when we come to speak of electricity. Rutherford was firmly convinced that all the atoms in the world could be built up out of these two components, the proton and the electron. And there my story begins.

"In his wide, lofty laboratory Lord Rutherford sat, considering, with much satisfaction, and a certain degree of excitement, the two parcels which he had received that day. One bore the letter P on its lid, and the other the letters El. And as he opened them he could not help laughing. There they were, in two glittering heaps—protons and electrons, fresh from the factory. They had been painted different colours, the better to distinguish them—the protons black and the electrons white. But

this was not really necessary, for, apart from their different charges, it was easy to distinguish them by their weight. The tiny black protons weighed like lead in the hand, while the white electrons were like dancing, iridescent soap-bubbles—silly, unreliable things.

"Lord Rutherford thoughtfully stroked his chin. Here they were again, the indistinguishable atoms, the ultimate, rigid building-stones of all that was, as Democritus had foreseen. But there were only two sorts, two protagonists: protons and electrons. And the scientist, taking a heavy black pellet, and a light white one, set the proton in the middle of the table, and the electron at a suitable distance from it. . . ." And here my host paused for a moment, and drew vigorously at his pipe.

"But what nonsense!" I said with conviction. "What nonsense! The two pellets would attract each other—strongly too, just as though they were connected by a spiral spring or a stretched elastic thread. Had Rutherford overlooked the electrical forces? The electron would rush irresistibly towards the proton. That would make a queer atom. . . ."



"Well, of course, Rutherford foresaw that difficulty. But, he thought, if I tie one of the pellets to an elastic thread, and swing it quickly round in a circle, then it will remain at some distance from my hand, in spite of the pull of the elastic. The centrifugal force will counterbalance the tension of the elastic. And so he gave his electron a light, graceful tap with the tip of his forefinger—and it began to encircle the proton. At a swift, uniform pace the white pellet described its orbit round

the black, heavy centre. The centrifugal force and the electrical attraction between the two were exactly in equilibrium. 'Now here,' said Rutherford, 'we have the lightest and the simplest of all substances: only *one* pellet of each sort.' It was the hydrogen atom that the scientist had made in this fashion. An atom of the gas hydrogen—the lightest and simplest stuff in the world. The primal atom, so to speak—the first rung of the ladder.

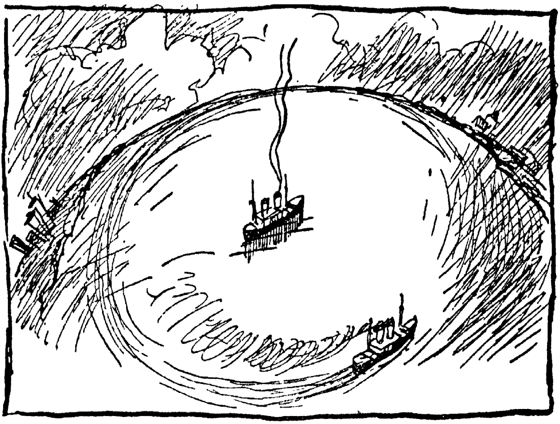
"You see, even the alleged indivisibility of the atom was a delusive notion, which misrepresented the facts: very much as a glowing ember, if whirled round and round in a circle, gives the credulous eye the convincing impression of a fiery hoop. But Rutherford had seen through the delusion. Really the atom consisted of nothing at all. Two tiny little points, revolving about each other at an enormous distance."

"Well, the distance can't be so very great," I ventured to interpose. "Atoms, after all, are not so immoderately large!"

"About a hundred-millionth of a centimetre in diameter. Ten millions of these atoms, laid side by side, would cover the length of a millimetre. That isn't much, I grant you—only the electron and the proton are so very much smaller. Imagine the Atlantic Ocean quite empty of shipping—except for one big liner, lying at anchor mid-way between Europe and America. Another vessel is steaming round it, in a circle which touches New York, the Equator, and Iceland. There is nothing else on the smooth surface of the water. There you have a picture of the limitless void which truly represents matter. Only in the immeasurable space of the starry heavens will you find a parallel, in the hopeless forlornness of the little suns, which move along their orbits in the cold, empty darkness, unthinkably remote from one another. . . ." My host paused again for a moment, as though to allow the curious picture which he had drawn to sink into my mind. And it was a singular picture! The earth, the table there before us, the smoke of my cigarette, my hands—all consist of atoms, of electricity, moving with terrific speed; of protons and electrons tearing round their orbits as far from one another as the two ships on the ocean! If one could take the protons and electrons of

which a man ultimately consists and pack them close together, one could easily contain them in a pin's head.

As though he had read my thoughts, the man of science began again, in his quiet, circumspect voice: "Rutherford was not dismayed. His lucid, scientific mind did not shrink from this singular picture of matter; he felt little of the sense of insecurity and uncertainty which inevitably seizes upon the normal mind when it is first confronted with this idea. The



great English physicist saw rather the magnificence of this animated prospect; the simplicity, the convincing lucidity and irrefutable logic of his conceptions. He rejoiced over this crazily whirling thing, the hydrogen atom, and resolved to continue his work of construction. It seemed to him that he had found the right path: To conceive the atom as a planetary system; to set a 'sun,' a heavy nucleus, in the centre, with the light electrons circling round it. He cast a rapid glance at the table of the Periodic System which hung on the wall: Helium, he saw, was No. 2; the 'noble gas' helium, atomic weight 4. And he took four of the glossy, black, heavy protons from the box and weighed them consideringly in his hand. The light electrons would not add sensibly to their weight. Four protons must form the nucleus of this atom; so much, he thought, was

proven. But a serious difficulty suddenly occurred to him: These four protons could never agree together. Four positive charges so close together—how could that be? They would mutually repel one another. And as he enclosed the four in his grasp he could feel their restless quivering, their mutual repulsion. It was as though he were holding a strongly compressed spring in his hand, so great was the pressure, so urgently did the four protons endeavour to avoid one another. There will be a catastrophe, thought Rutherford, with concern; the helium nucleus will fly asunder before it is fairly constructed! This will never do!

"And there was yet another problem to be considered: An ordinary atom of helium is electrically neutral as regards the outer world; it behaves precisely like an uncharged particle. This means, apparently, that the four black pellets must be accompanied by four white ones—four protons by four electrons—so that there shall be no surplus charge, either positive or negative. Well and good. But all the other physical data imperatively require that only two electrons shall revolve about the helium nucleus. Hydrogen has been observed in which an electron is lacking: a 'hydrogen ion,' identical with the proton. Helium has been discovered in which one or even two negative charges are wanting—but never more than two. What on earth was Rutherford to do with the two superfluous electrons?

"These difficulties worried Lord Rutherford. In any event, the helium nucleus was more complicated than he had imagined. He tried to evade the difficulty then—this was in 1911—in a very ingenious manner: it seemed to him that two electrons would have to be 'baked in' with the protons. But today the physicists take a slightly different view of the problem."

The scientist leant back in his chair. He was silent for a while. Then he lit his pipe again, and looked at me inquiringly. "Now do you think I might give Lord Rutherford a little help at this point? Shall I enter his laboratory in the guise of a *deus ex machina*, with the knowledge of the year 1934, and give him a few words of advice?"

"Why, yes—but what can you do to help him?"

"Well, I should give him a box of neutrons."

"Neutrons?"

"Yes. Chadwick discovered, in 1932, that there are such things as neutrons. They are tiny, electrically neutral particles, which have much the same weight as protons.

"It is quite possible that Rutherford—doubtfully at first, and then enthusiastically welcoming this new possibility—tried his own hand at manufacturing neutrons. He pressed an electron and a proton together; there was a faint click, such as you hear when you fasten a press-button—and the two were permanently united.

"The positive and negative charges are now mutually satisfied. Externally, the pair is mutual. Its weight is approximately that of the proton—you will remember that the electron is two thousand times lighter than the proton, so that it contributes hardly anything to the weight of what Chadwick called a neutron.

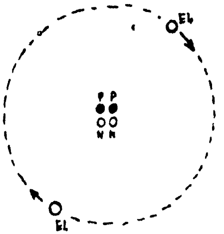
"The existence of the neutron is indisputable. It is possible, of course, that a neutron is really built up as I have described—that it may arise from the conjunction of an electron and a proton. There are many theoretical reasons for believing that it may be so. Of course, it is also within the bounds of possibility that the neutron is a 'genuine' elementary particle, not built up in any way, and that Rutherford would have to send to the factory for a box of neutrons before he could get on with his building. But the nature of neutrons need not concern us now; the point is, I should give him some.

"And then I should strike a becoming attitude, and make a little speech, much as follows:

" 'Your investigations, Lord Rutherford, of radio-activity and the structure of atoms have been of decisive importance in the evolution of the new physics. We have learned much that is new, but we have also grown more modest. We know that the normal physical conditions no longer hold good in the nucleus of the atom. All sorts of things may be possible there: but we may doubt whether the familiar laws and equations of physics apply to it. It is too early as yet for specialized and definite conceptions. We must content ourselves today

with the hypothesis that protons and neutrons exist side by side in the nucleus, and that they are held together there by forces of some kind—the non-committal term 'reciprocal forces,' which we use to define them, is fairly descriptive of our attitude. Outside the nucleus, between the nucleus and the electron, we shall regard the old laws of physics as still valid.'

"The new conceptions are a simplification of Rutherford's original model; indeed, they deprive it of much of its attractive lucidity. They were made possible—let us once more emphasize the fact—only by the discovery of the neutron. And we must not forget that Rutherford played a decisive part in the development of the new physics. Now he was able to get on with his work.



"He laid two of the four protons back in their box and replaced them by the dull, grey, merely heavy neutrons. He was confident that the reciprocal forces would hold the whole nucleus together. The helium nucleus was still complicated enough, for it now comprised two protons and two neutrons. Still, the original difficulties had been overcome. And so, taking two electrons, with the same inimitable sweep of the hand as before, he set them rapidly circling round the nucleus. There it was, a working model of helium. The weight was 4, as the Periodic System required. Two outer electrons—and thus, at most, two negative charges would be lacking, as was confirmed by observation.

"Now the way was clear before him—the way to build up a universe. The notion that the helium nucleus, despite its undoubtedly enormous powers of resistance, its great stability, was yet a built-up structure, was decisive. Step by step the scientist disposed of the other elements. He played and juggled with protons, neutrons, and electrons; but the process was really quite simple. With each successive element a new outer electron was added—and with each successive element the number of protons in the nucleus was increased by one. But the nucleus also received an increasing number of neutrons,

for at first the atomic weight increased twice as quickly as the number of outer electrons, and later on even more rapidly. The atomic weight of element No. 6, for example (which had six circling electrons, weighing next to nothing), was 12, so there were twelve heavy pellets in its nucleus; six protons and six neutrons.

"So Lord Rutherford sat in his laboratory and built up his world; and by the evening he had come to the end. With his practised hands he fitted together the monumental structure of the last element, uranium. Ninety-two protons and a hundred and forty-six neutrons made up the nucleus, while ninety-two electrons, light as soap-bubbles, surrounded the monster nucleus at progressively increasing distances, ready to dance away at a sign from their creator. And with the old inimitable touch Lord Rutherford set them revolving in their orbits, rose to his feet, and left the laboratory."

"There's one thing I don't understand," I interposed. "Why should the helium nucleus in particular be so important?"

Instead of answering me, my host got up and fetched one of the big books that were lying on his desk.

"Here you see the famous table which Rutherford had before him during his task of construction: the Periodic System of the Elements. And now, compare the weights of a few elements:

Series number in Periodic System ..	9	11	13	15
Element	Fluorine	Sodium	Aluminium	Phosphorus
Number of Protons (Charges on nucleus)	9	11	13	15
Number of Neutrons..	10	12	14	16
Atomic Weight: Protons + Neutrons	19	23	27	31

"If you remember that the weight of the helium nucleus is 4, I don't think I need say anything further. Each of these elements is produced by the addition of one helium nucleus to the former element, whose number, in the Periodic System, is less by 2. In the heavier nuclei the protons and neutrons seem inclined to combine into groups of four, into helium

nuclei. It just happens to be an especially successful and mysteriously tenacious structure." My host was silent.

"So that was the creation of the Universe?" I asked.

"Well, naturally, we can't know how it really came about. It is possible, of course, that somewhere, at some time, in the depths of space, the electrons and protons, flying aimlessly to and fro, encountered one another, and so united. But that's not the end of the fairy-tale. The tragic imbroglio is yet to follow. So, listen:

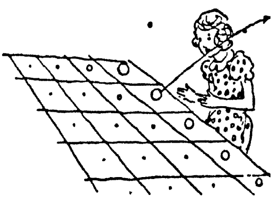
"Rutherford had discovered Nature's secret, and had imitated her method of building up her materials. They were all made of the three sorts of things: protons, neutrons, and electrons. Every element has two specific numbers: its atomic weight—the sum of the neutrons and protons in its nucleus —and its serial number—the number of the protons alone: of the charges of electricity on the nucleus.

"And if we consider Rutherford's mode of construction, we cannot doubt which number he would think the more important. *The number of charges on the nucleus is the number which determines the order of the elements.* An element which proves to have six protons in its nucleus and has six electrons dancing round it is given place 6 in the Periodic System, and is known as Carbon. In comparison with this number the atomic weight has little significance, although it was with its help that Mendeleieff and Meyer first discovered the Periodic System.

"Well, there lay the models of the elements, so cleverly and beautifully constructed, from hydrogen to uranium—the whole series of ninety-two. Suddenly the door opened, and in came Mary Ann, the youngest child of the family. In amazement she gazed at the whirling figures, and inquisitively bent over one that was especially large and handsome—the element No. 88, atomic weight 226: radium. And then something terrible happened. Suddenly a helium nucleus shot out with terrific energy, whizzing past the child's ear, right across the lofty room, and dashed against the table of the Periodic System which was hanging on the wall. With a loud bang it fell to the floor. The two outermost iridescent electrons of the radium, now deprived of their corresponding counterweight in the nucleus—for it was just the two positive charges of the

truant helium-nucleus that had kept them where they were—danced uncertainly to and fro for a while, and then took their departure. What was left? A structure with 86 circling electrons, atomic weight 222. And Lord Rutherford, who came rushing into the room, sternly inquired: 'How does this radium emanation come here?'—for that was the name he gave to an atom with 86 electrons, and an atomic weight of 222. 'And where has my radium gone?' Yes, where was the radium?

"It had disintegrated! Somehow, no one could say how, it had spontaneously disintegrated, turning into another element. There was no doubt about this: the disintegration-product was as good a radium-emanation atom as Lord Rutherford himself could ever have made.



"Startled and wearied, Lord Rutherford sank into a chair. He had arranged his elements so neatly in their Periodic System, but now the whole thing was spoilt. True, the lighter elements were behaving in a normal fashion. But the heavy ones, all those that chemistry calls the radio-active elements, were quite out of control. The α-particles, the helium nuclei, were breaking away from their nuclei—and at once the element, its charge diminished by two protons, moved two places to the left in the Periodic System!

"Or they violently shot an electron out of their nucleus, a β-particle. But where did the electron come from? Probably a neutron had suddenly disintegrated into a proton and an electron, and had flung the electron out of the nucleus. The flying electron carried its negative charge out of the nucleus: the other half of the disintegrated neutron, the proton, was left behind. But this meant that the number of protons, the number of electrical charges, and therefore the serial number in the Periodic System, was increased by 1 through this disintegration, and thereupon the element jumped one division to the right! Finally, to set matters in order, an electron that happened to come wandering by was captured and given a

Radium Disintegration

(Half-value Period)

Radium

1,580 years
$\downarrow \alpha$
Radium-

emanation

3·85 days
$\downarrow$
Radium A

3.05 min.
$\downarrow \alpha$
Radium B

26·8 min.
$\downarrow \beta\gamma$
Radium C

19·5 min.
$\beta\gamma \swarrow$ $\searrow \alpha$
Rad. C′ Rad. C″

1 millionth sec. 1·32 min.
$\alpha \searrow$ $\swarrow \beta\gamma$
Radium D

16 years
$\downarrow \beta\gamma$
Radium E

4·85 days
$\downarrow \beta\gamma$
Radium F

(Polonium)

136·5 days
$\downarrow \alpha$
Radium G

(Lead.)

Stable.

place in the outer shell. And as if that wasn't enough, a lot of these fellows, released by this disintegration, formed a sort of Röntgen-ray in the neighbourhood of the element—a γ-radiation. No, this was anything but a peaceful state of affairs!

"But slowly Lord Rutherford composed himself. To be sure, things were flying about in a perfectly crazy manner, but after all, apart from their exasperating unreliability, these radium elements had their uses. And then he saw how the radium emanation, after a series of further jumps, turned into Element 82, and then was quiet. And Element 82 was *lead*! This seemed to be the end of the transmutations. For this was certain: there was always a disintegration, a splitting up of the nucleus, never a building up; and after the elements had passed through many intermediate stages, and had sent out their α- and β- and γ-radiations, they all ended in Element 82—they turned into lead. But the lead remained stable. Here finality was reached; with the ultimate transmutation into lead their aberrations were ended. Lead remained lead. But there was still one little difficulty to be overcome. The radium-lead was lighter than ordinary lead —instead of 207·2 it weighed

only 206. This troubled Lord Rutherford at first, and he sent a specimen of the metal to his friend the chemist, asking him to examine it. The answer was prompt: it was undoubtedly lead. He had tried all the dodges known to chemistry, but apart from the difference of weight he could not distinguish the radium-lead from ordinary lead. And he proposed to call the two kinds of lead 'isotopes,' which means, 'having the same position'; for they obviously had to be given the same place in the Periodic System—place No. 82. With this Rutherford agreed.

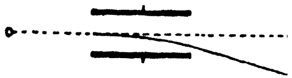
"The problem of the isotopes—these substances with the same nucleus-charge but different atomic weights—had to be elucidated, and the explanation dispelled the last lingering doubts. As we have described the building up of the elements, we might and indeed should have expected that all the atomic weights would be whole numbers. But here, for example, is chlorine, with atomic weight 35·5. A hard nut to crack! One could hardly assume that the chlorine nucleus contained 35·5 protons and neutrons. Well, two different isotopes of chlorine have been discovered—chlorine twins, so to speak—which in appearance, and in all their physical and chemical reactions, simply cannot be distinguished; only their atomic weights are different. The atomic weight of the one is 35, of the other 37. Wherever we find chlorine we find representatives of both varieties, always mingled in the same ratios (3 : 1), and so the enigmatic value 35·5 proves to be simply the weight of the *mixture*.

"Today all the elements are shown to be mixtures of different isotopes. Neon, for example, the red-glowing 'noble' gas, has two isotopes, 20 and 22; and the year before last G. Hertz, in Charlottenburg, by months of pumping with a battery of thirty-six mercury air-pumps, actually managed to separate these unequally heavy gases, and so furnished a practical and irrefutable proof of the theory—if such was needed. Even hydrogen is not exempt. In 5,000 ordinary hydrogen atoms there is always one atom of atomic weight 2—an atom of 'heavy' hydrogen, which, when combined with oxygen, forms the 'heavy water' of which we have heard so much.

"The isotope-hunter among the physicists is Aston, an

English scientist. He sends the atoms through an electric and a magnetic field, in which they are turned aside—you might almost say, blown out of their course—and then allows them to fall on a photographic plate, where they produce a black streak. The light atoms are naturally turned aside more than the others, just as if you throw a ball of paper it is blown aside by the wind farther than a stone would be; and accordingly the streak made by the lighter isotopes is displaced farther than that made by the heavier atoms. No isotope on earth can elude Aston's test.

"But Lord Rutherford saw that his original fears had been exaggerated. Everything was in perfect order after all. True, some of the heavy elements had the mysterious faculty of spontaneously disintegrating and emitting radiations; apparently their complex nuclei were not sufficiently stable. But the chemical and physical character of an element was definitely determined by the numerical value of the nucleus charge, the number of protons, and the normally equal number of the outer electrons. As we have seen: *the charge on the nucleus determines the position of the element in the Periodic System.* And now it appeared that the atomic weight was of secondary, almost of casual importance. And so the fairy-tale, that once seemed so full of peril, ends in the triumph of science, and the criminal archives of the chemists are correct after all! But please do not forget that this was just a fairy-tale, no more! No one has ever seen a proton, or held it in his hand!"

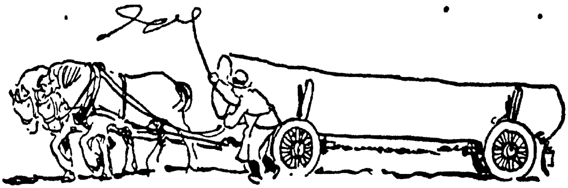


The scientist spoke no more; he gazed at the thin, twisting thread of smoke that was rising from his pipe, and losing itself in the darkness of the room, and there dissolving. For a long while we were both silent. I could not get the singular picture which he had drawn for me out of my head—the picture of "empty matter."

II. THE DIRECTION OF THE WORLD-PROCESS

A RUSH of white hissing steam, and the driver pulls the lever. Creaking and groaning, the heavy express locomotive begins to move. Quite slowly the long row of cars glides out of the station, quickens its pace, and disappears from sight round the curve.

Why does the train move so slowly? Why doesn't it dash away immediately at the rate of sixty miles an hour?—Because



of its *inertia*. Force is needed in order to set a heavy car in motion. Once it is moving it rolls on almost of itself. Every body wants to maintain its velocity at any moment unaltered —even if this is "Velocity 0"—that is, motionless rest. This law is known as the *law of inertia*—and its first discovery was one of the most important achievements of Galileo. A suit-case that suddenly falls off the baggage-rack when the brakes are applied has no evil intentions; it is merely obeying the law of inertia.

But why does the train move at all?—The engine-driver, by pulling the throttle-lever, allows high-pressure steam to enter the cylinders. Now the steam presses against the walls of the cylinders and the pistons. A molecule of water-vapour weighs 0·000 000 000 000 000 000 000 028 of a gramme. If a single molecule were to strike against the great piston of an express locomotive the piston would not move. Of course, not one molecule only, not even 10,000, but billions and quadrillions are imprisoned in the cylinder, dashing against the piston and flying back from it. But all taken together, they don't weigh

a pound. Something else must be at work. The pressure?—But what is it that causes the pressure?

Energy and Impulse

A rifle-bullet weighs a fraction of an ounce, and nothing happens to it if we let it fall on the ground. But if we fire it against a steel armour-plate, or a rock, at a muzzle velocity of 2,000 feet per second, it will be squashed as flat as if we had put it under a steam-hammer. It has crushed itself by its own velocity.

The energy which the gases of exploding powder generated in order to accelerate the bullet—in order to set the resting bullet in motion—was, in a sense, carried off by the bullet, and it will give out this energy again if it is stopped. If you have ever loaded an air-gun you will have some idea of the considerable energy which is stored up, and released on pulling the trigger. And not long ago a physicist—who had, of course, another object in view—performed an experiment in which this energy was recovered. He shot a bullet into a second rifle-barrel. The compressed air shot it out again with almost the same velocity, and it oscillated to and fro between the two rifle-barrels until the loss of energy through friction brought it to a standstill. In this comparatively obvious case it is easy to follow the conservation of the energy. One can almost feel how the energy of the compressed air—*potential* energy, we call it—is continually, though very quickly, in the fraction of a second, transformed into the movement-energy, the *kinetic energy*, of the bullet.

We all have some notion of what is meant by the energy of the bullet; but the physicist has not only a notion of it—he has an equation for it, and he writes it down thus:

$$\text{Energy} = \tfrac{1}{2} \times \text{Mass} \times \text{Velocity} \times \text{Velocity, or } E = \tfrac{1}{2}mv^2.$$

A sprinter on the cinder-track will cover ten metres a second; if he weighs a hundred kilogrammes his energy of movement will be $\frac{1}{2} \times 100 \times 10 \times 10 = 5{,}000$ "Joules," as the *unit of energy* is called. This energy would suffice to lift 500 kg. to the height of one metre (a motor which generates the same

amount of energy every second would be giving out 7 H.P.). If the sprinter could run twice as fast his energy would be four times as great: $\frac{1}{2} \times 100 \times 20 \times 20$ Joules. You see, the athlete may be said to work pretty hard!

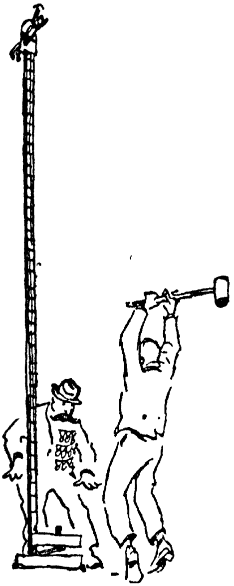
Here is a second useful notion: *Impulse*. This, too, can be defined by a simple equation: Impulse = Mass × Velocity. The impulse of the sprinter is $100 \times 10 = 1{,}000$, and the impulse, too, depends on the velocity. If the sprinter, as he tears along the track, should unexpectedly jostle a bystander, and push him violently aside, thereby losing pace, this may be an unpleasant incident for the persons concerned. The physicist merely states that the runner, by the collision, has conveyed part of his impulse to his friend. He has lost a little of his velocity, and his impulse is therefore a little less than before; but his friend has involuntarily acquired a little impulse; if he was previously standing still, he had a little velocity after receiving the blow.

It was a long while before people learned to distinguish between impulse and energy. Newton and Leibniz, both of whom may be supposed to have known something of physics, disputed for years over these two values, and they were really talking at cross purposes all the time.

For both impulse and energy, however, the *principle of conservation* is valid. In a closed system—which means, in some part of the Universe unaffected by the action of external influences—or the Universe itself, or the solar system, or even the locomotive-cylinder with its molecules of water-vapour—the total impulse and total energy are conserved so long as they are left in peace; they neither increase nor diminish. These are two laws which are always and everywhere fundamental in physics: they are dogmas, unassailable truths. As in a country whose frontiers are closed, the total wealth remains constant, though money may constantly pass from one inhabitant to another, so energy and impulse may be constantly redistributed, but the total amount does not vary

so long as nothing is borrowed from outside—so long as the system is a *closed* one.

The other day, at a fair, I saw a hefty fellow "trying his strength" with the mallet. He struck the block with terrific energy, so that the heavy iron slider flew right off the vertical scale, stood still for a split second in the air—and now it had only potential energy!—and then, swiftly falling, landed full on the left foot of the hero, who was gazing upwards as though spellbound, amazed by his own performance. He swore lustily as he hobbled away, and I, as a physicist, was tempted to reproach him with the purposelessness of his proceeding. Apart from slight losses by friction, he would have achieved exactly the same result, without the complication of a twofold transformation of energy, if he had struck his foot directly with the mallet—quantitatively the same result! But evidently he knew nothing about the principle of the conservation of energy.



What is Heat?

Now—to return to our subject—we understand where the pressure comes from. It is the result of velocity. The gas-molecules have a velocity which is roughly equal to that of a rifle-bullet—a velocity of several hundred metres per second. So their impulse, despite their trifling weight, may acquire a quite respectable value, and every gas-molecule transfers its impulse to the piston when it dashes against it and is hurled back. The sum of the impulses transferred in one second, the constant, rattling drumfire, has the gross effect of an irresistible

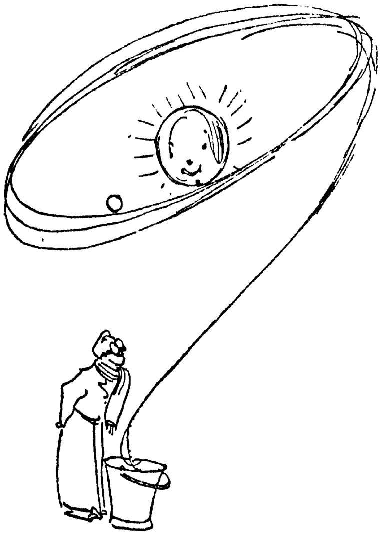
pressure, and with a sigh the piston begins to move. It is like a person who is collecting farthings—ridiculously small coins, but he collects them diligently and continually; and each of the quadrillions of molecules drops something into its box, not once, but many hundreds of times in the course of a second. So at last a considerable sum results, a pressure of several tons, enough to set a whole train in motion.

A very old experiment proves that heat is increased by pressure. Evidently the mass of the molecules cannot be increased by pressure, but their velocity and therewith their momentum will increase. This conclusion was reached by the celebrated German physicists, Boltzmann and Clausius: With rising temperature the velocity of the molecules increases. They boldly went a step farther, and declared: The two concepts are inseparable. *What we call heat is nothing more than the kinetic energy of the molecules.* To heat a gas means to increase the kinetic energy—that is, the velocity of the molecules; to cool it is to retard the velocity of the molecules.

A strange and unfamiliar notion, to which one has to grow accustomed. But really there is no difference between the two things. If we could load a machine-gun with molecules and fire them off with a velocity of 500 metres per second, this sheaf of molecule-projectiles would have a temperature of 25° C. If we fire them off with a velocity of 1,000 metres per second the temperature would be 40°. Of course, in a gas at a temperature of 25° by no means all the molecules have precisely the same velocity of 500 metres per second. Some have a higher, some a lower velocity; but the *average* velocity will be 500 metres. More than that we cannot say.

So much for the "kinetic theory of gases." It explains all the properties of the gases. There are 606,000 milliard milliard or 606,000 trillion molecules in a couple of grammes of hydrogen; so in four gallons—a big bucketful—there would be . . . It is simply impossible to form any notion of such inflated figures. But if one were to mould the whole Earth into skittle-balls, one would arrive at much the same number.—Suppose we exhaust the air in a glass globe. With our best air-pump we suck the air out of it. The barometer which measures the

pressure in the globe falls—from 760 mm. to 1 mm., and from 1 mm. to 1 millionth of a millimetre. Such an exhausted globe is practically empty of air—but it still contains about two milliards of molecules to the cubic centimetre, or about as many as there are human beings upon the Earth. Ten million hydrogen molecules set side by side would cover one millimetre. If we could string together all the molecules in one bucket of water, like so many beads in a necklace, we should get a string over 60 milliard kilometres—over 37 milliard miles—in length: long enough to go about seventy times round the Earth's orbit! That will tell you something about the molecules! Nevertheless, we shall probe into the depths of their being, and sooner or later we shall try to learn something of their individual biographies.

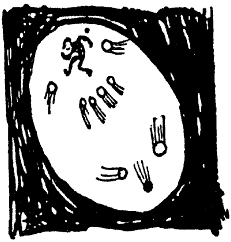


The Micro-Man
An incredible Story

A Frenchman once wrote a book which described how a man was diminished, by some drastic medical treatment, until he was smaller than the tiniest bacillus—far below the limits of visibility—smaller even than a molecule. That is going too far. We will stop the fellow—shall we call him George?—when he is still a few thousandths of a millimetre in height, and we will wait and see what becomes of him.

In the brightly illuminated circle of the microscope you can see George quite plainly. He is hovering in space, very slowly, very gracefully sinking through the field of vision. You can hardly say that he is falling; for such microscopic beings the friction of the air plays a very important part, and he sinks as slowly as a particle of dust, or a tiny scrap of tissue-paper, because his weight, compared with his surface, is a very small quantity indeed. A little twist of the micrometer focussing-screw, and we have him sharply in focus again. But—he is trembling.

"Are you afraid?" we telephone down to him. "There's nothing to be afraid of!"—"No!" he answers: "I'm not trembling—I'm being trembled!"



And so he is. The tiny human figure is lurching hither and thither as though tugged by irresistible hands. Following a wild, zigzag course, now running in this direction, now in that, for a few seconds he stands motionless, and then, with redoubled energy, he suddenly leaps a whole millimetre. It really seems hardly considerate, and it is also very difficult, to keep him in the field of vision. "Do keep still!" we cry, rather impatiently. But it is useless; George is shooting to and fro like a water-flea.—"It's the molecules, you know! They won't leave me in peace! I believe I'm bruised all over my body. They keep on rattling against me, now from above, now from below, and now from all sides at once—and then I am able to stand still. And a little while ago a whole swarm came from the right of me, and by chance none at all from the left; did you see how they threw me about? They are simply playing football with me!"

A curious fragrance is spreading through the room, an odour of snuff and lavender. An old gentleman, who stoops a little, carefully dressed, with a grey top-hat and well-tended whiskers, is regarding us with a smile. How the deuce did he come through the closed door?—"Brown is my name," he says. "I was formerly a botanist—dear,

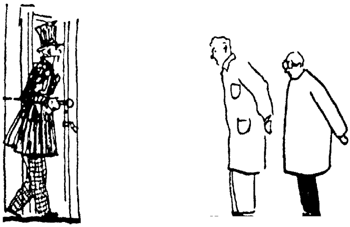
dear, that was a good hundred years ago. In the time of Dickens."

"Brownian movement?" I ask, doubtfully.

"Ah, you know me! So much the better. Yes, yes; I don't wish to boast, but I did, as a matter of fact, detect those tremulous movements, long before ever you were born."

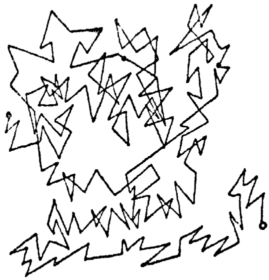
"And is there no possible means of helping our friend George?"

"No—but why? My spores and pollen-grains danced and quivered in just the same way. It did not harm them. By no means. May I just have a look?" And he bends over the microscope.—"Splendid," he says: "There were not such good microscopes in my time." He thoughtfully nods his head, and straightens himself again.



"And so it is happening to your friend! The sport of chance! Personified chance, if you will. Absolutely incalculable!" He steps back and takes a pinch of snuff.—"But no, not incalculable," says the third man, who has been sitting all this while in silence. "Think of the calculations of Einstein and von Smoluchowsky—think of the kinetic theory of gases!"—"I know nothing about them," the old gentleman grumbles.—"That is not surprising; they are among the achievements of the last fifty years."—"But you do know, Mr. Brown, why our George is quivering like that?"—"Well, I have my ideas about it," said the old man, cautiously, as he took the chair that was offered him. "But what were you saying about the kinetic theory, as I think you call it? It interests me to hear what people have made of my discovery since my time on earth. I have not many opportunities of hearing about such things."—"Well, we know today that the Brownian movement, this constant quivering movement, like the dancing of motes in a ray of sunlight, is caused by the blows of the molecules of the air."—"Molecules? Ah, my friend Dalton has told me

something about them," interrupted Mr. Brown.—"So he was right! And what else?"—"I was only going to say—my little friend down there is not so absolutely 'fortuitous' in his movements. I don't know, of course, exactly how he is going to move next moment, but I do know what the average extent of his movements must be. I know even more than that. If I heat the air on the right of the field of vision, he will be slowly driven towards the left, for then swifter and more energetic molecules will strike upon him from the right. One could even bring him to a standstill if one wanted to. It would only be necessary to freeze him in."—"What do you say?"—"You see for yourself, the warmer it is, the quicker the movements of the molecules, and he trembles more violently. And the lower the temperature sinks—suppose I surround him with a freezing-mixture—the slower the movements of the molecules. The temperature might fall until there was no energy left in the molecules—until they lost their power of movement, until they crawled wearily to and fro, and at last came to a standstill. Then the point would be reached when the temperature could sink no lower—the absolute zero—273·16° Centigrade. We haven't quite reached it yet; indeed, we can't quite reach it. A theoretical consideration—the heat principle of Nernst—makes it impossible. But we have already got to within a few hundredths of a degree of the bottom.



Brownian Movement

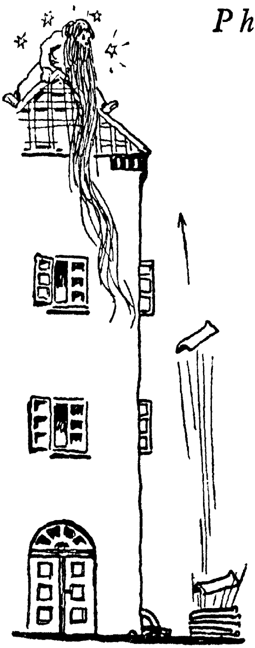
"As the molecules are colliding with our friend down there, and making him tremble, so they also collide with one another. They wander about, making mutual exchanges of energy, since the quicker molecules give up a little of their impulse to the slower, and this continues until all is in equilibrium. Until the conduction of heat ceases—until all have the same average velocity, the same temperature."

"Wonderful!" cried the old gentleman with enthusiasm, bending forward in his chair. "But tell me, what special notions

have you of the form of the molecules, of their appearance, and what happens in the individual molecule when it collides with another?" But the person addressed shook his head.

"Well, you see, we work according to *statistical* methods. We don't want to know what the individual molecule is doing, or how a collision affects an individual—we concentrate rather on the great mass, the average. And in this way we have discovered exact laws for the average behaviour of a gas. Laws of heat-conduction, pressure, and gaseous friction. The Brownian movement, to which my comrade down there is subject, is a special case, in which comparatively few molecules are concerned. Hence the apparently purposeless behaviour, which now, of course, we can control. We have taken chance into custody!"

The Direction of Natural Phenomena



"And the kinetic theory has told us more: it has taught us something about the direction of natural processes. It is just thinkable that our friend in the field of the microscope might at an exceptional moment be flung a distance of thirty yards, because for once a great swarm of molecules had struck him on one side, and none on the other. That is thinkable—but improbable in the highest degree. It would be just as possible that the many little blows of the molecules might for once be so directed that the temperature would rise instead of falling; that an ice-block would give out heat, and make a bar of red-hot iron still hotter.

It is *possible* that a tile might of

itself fly up from the street into the hand of a tiler on the roof—driven upwards by the chance blows of the molecules. Perrin has calculated the probability of this pleasing event. His result is rather discouraging for the tiler, who would grow old and grey if he waited for it to happen. Such a thing occurs once in $10^{10,000,000,000}$ years. That is a digit with 10 milliard noughts after it—a number which, if it were written down, would fill 20,000 books the size of this volume. The age of the earth is a tiny fraction of this period; the whole Universe has not existed so long.

"If I pour a blue and a yellow powder together and shake them well I get a green powder. It is *thinkable* that if I went on shaking them the blue and yellow would once more appear quite clearly separated. But . . . is it probable?"—"No, improbable," replied our guest very earnestly. He was completely captivated by the wonderful development of physics to which his discovery had given the stimulus.—"But that is something quite new in physics! Mechanics tells us nothing of the *direction* of natural processes. The theory of gravitation would allow the Earth to revolve round the Sun in the reverse direction. Just why the Earth has chosen this direction is its own business, and has no ulterior importance."—"Precisely. Perhaps we had better say, more correctly: Physics is acquainted with a great number of processes which could just as well, and just as intelligibly, in a physical sense, occur the other way round. While a stone falls to the ground with ever-increasing velocity, we have also the reverse process: if it is thrown upwards it rises more and more slowly. It is only necessary to reverse the sign of one of the terms of the equation—in that case, the time. But there are processes which can run only in one direction. Irreversible, we call them. They are always processes with a large number of partners, in which a sort of mixture is involved, and in which *chance* plays a part. For the very notion of admixture implies that the element of chance is present. A typical example of this is the equalization of temperature in a gas, in which a certain order prevails in the beginning; the swift 'hot' molecules on the left, the slow 'cold' molecules on the right. This order will be destroyed by the thorough commingling of the two sorts of molecules. Most

of the actual processes in the world are of this kind—whether I drink a glass of brandy, or make experiments in the conduction of heat. Nature loves absolute uniformity, and disorder, and admixture. In all her processes she works in such a way that she reaches this goal. *By this the direction of the process, and its duration—its time—is determined.*

"An ocean steamer ploughing its way through the Atlantic develops the full power of its engines even in calm weather. Twenty-thousand horses are raging in its bowels. And they are taxed to the full to drive the ship forward against the resistance of the water. The whole of the engine-power is ultimately lost in friction, in the friction of the water against the hull of the ship as it rushes past, or the internal friction of the water when the waves and the eddying wake of the propellers gradually die down to rest. The steamer is fundamentally a stove which heats the ocean. But one has never heard of a case in which the energy of friction that is now contained in the ocean was so obliging as to drive a ship across the Atlantic and in so doing cool the ocean. Here we have the irreversibility of Nature—the second fundamental proposition, as we say."

"Why the second?" Mr. Brown wants to know. "What is the first?"—"The first fundamental proposition is that of the conservation of energy—the energy principle. That mechanical energy is conserved we have known for a long time. But a South German physician, Julius Robert Mayer, was the first to recognize—in 1842—that this principle is still valid for the transformation of mechanical into heat energy. The savages make fire by rubbing two sticks together—and all the work they do, the whole of the energy they expend, is transformed into the heat-energy of the sticks. It was while he was on a voyage through the tropics that Mayer had a convincing intuition of this fact—'for once in his life he was a genius.' Joule confirmed the principle by experiment; Helmholtz gave it lucid mathematical expression, and added that it was universally valid. Whether the energy is mechanical, chemical, electrical, or thermal, the principle of the conservation of

energy still holds good; the energy may disguise itself to the point of being unrecognizable, but its amount always remains the same; it is one and the same thing in another form.

"*In all the processes of the Universe the sum of energy remains constant. Energy can be neither created nor destroyed—there is as much today as there was a thousand years ago, and as there will be throughout all the future.*

"It follows from the first proposition that a machine which creates energy out of nothing is inconceivable. 'Perpetual motion' is impossible. *Ex nihil nihil fit.*

"Today we believe this principle of physics without more ado —but let us realize that it is a matter of faith. It cannot be proved, unless we see a proof in the fact that for centuries the cleverest thinkers tried in vain to invent a *perpetuum mobile.* To the Middle Ages, apparently, our modern dogma, the 'energy principle,' never occurred. It was not by mere chance that the Middle Ages saw no difficulty in believing—for example—that young eels were born quite spontaneously from the mud."

"But surely your ship that takes the heat-energy from the ocean and transmutes it into speed does not contradict the first proposition!"

"Nevertheless, believe me, this ship is impossible. You may be sure of this—not only do we know of no such miracle-ship today, but such a ship will never be. All attempts in this direction have failed. And today we know for certain that there will never be a *perpetuum mobile* of the second kind; but this, too, is a matter of faith!"

Mr. Brown did not seem to be convinced.

"I grant you," said the other, "that for the general thinker the second energy-principle is not as obvious as the first: *it is fundamentally impossible that heat should be completely transformed into work: a portion always remains heat and tends towards a lower temperature.*—Well, whether we like it or not we must believe the research-workers, who, basing their experiments on this thesis, have achieved the most incredible results in physics and chemistry, and in physico-chemistry. But in accepting it we have to overcome an inner resistance: we do not believe it cheerfully and as a matter of course, but rather because proof to the contrary is lacking. We have here

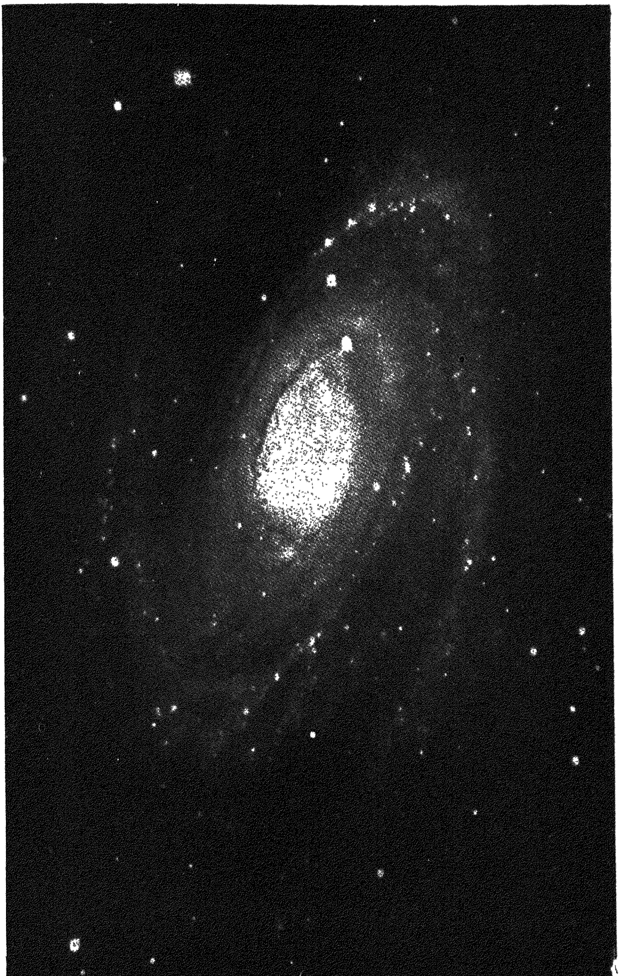
no acquittal on the grounds of innocence proven, but rather an acquittal because evidence of guilt is insufficient. Only the physicists, who have done an enormous amount of work in connection with thermodynamics and the kinetic theory, have really got over this doubt.

"The direction of the natural processes is closely bound up with the second main proposition. The molecules of a gas go tearing past one another in a seemingly wilful and meaningless manner—and yet their total movement is such that the heat of the gas is diminished—the temperature falls. The process, as we have said, tends to replace order by disorder; Boltzmann expressed the same notion in a somewhat different manner when he said that the disordered state is more probable than the ordered, and that Nature always tends towards the state of the greatest probability. He introduced a new mathematical function, *entropy*,[1] which represents a measure of probability; and with the help of this notion the second fundamental proposition can be stated in this simple form: *The entropy of the Universe is constantly increasing*. Nature has a levelling tendency—she de-values energy, inasmuch as she deprives it of its differences. We just have to get used to this idea; all the same, we believe that we have discovered something very singular in this principle of entropy. For consider: we have to accept the Newtonian theory of gravitation, or the size of the Earth, without arguing about it. An Earth ten times the size of ours would be quite thinkable, and so would a theory of gravitation according to which the force of attraction would diminish in accordance with the fourth or fifth power of the distance, instead of with the square of the distance, as Newton demonstrated. Nature has here once and for all chosen one definite dimension out of all the theoretically possible dimensions: by chance, as it seems to us.

"But it is otherwise with the principle of entropy. Its validity seems to be less fortuitous; it seems inevitable. It is an alien in the realm of theoretical physics. A great mystery envelops it—the mystery of Time! And it seems to know more about Time than the other principles—and to know other

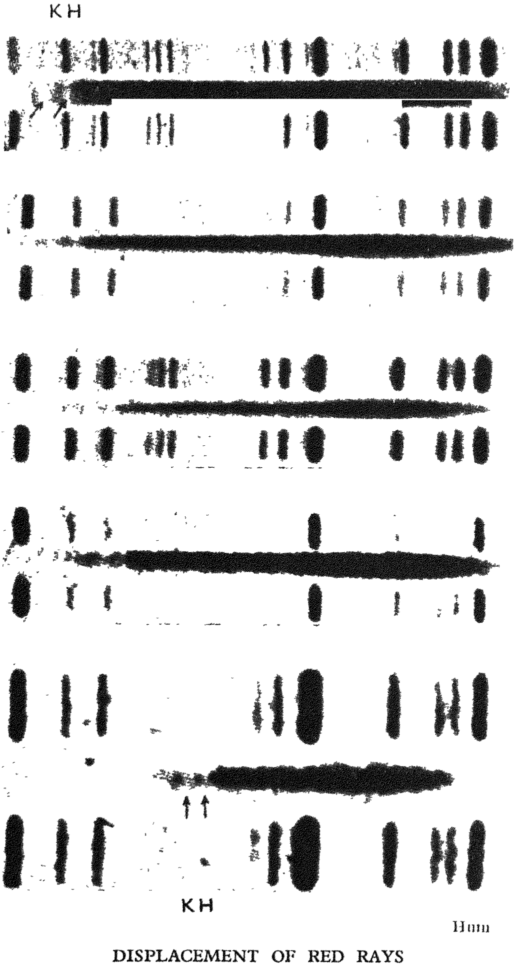
[1] Entropy = a measure of the unavailable energy in a thermodynamic system.

PLATE I



SPIRAL NEBULA NGC 3031 IN THE GREAT BEAR

PLATE 2



DISPLACEMENT OF RED RAYS

Spectra of Nebulae, photographed with the 2·5-metre Reflecting Telescope.

things. With cold and paralysing ruthlessness it imposes its will upon life. It determines the direction of the world-process. The entropy of the Universe is increasing!"

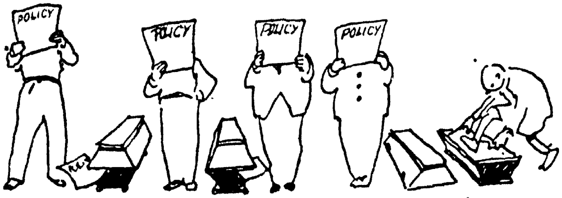
The old man nodded in silence, and took a pinch of snuff.

"May I for a moment go back to what I said a little while ago? The kinetics of the gases is the region where statistical methods, with their great intellectual difficulties, made their first appearance in physics. We simply don't attempt to learn what the individual molecule is doing, or what happens to it. In Boltzmann's day one would have repudiated the very idea that we should ever be able to see a single molecule. Today we are well on the way to doing so. And we think the notions of molecular impacts may contain a great deal of truth. But we put them on one side. We also put aside all our notions of the form and appearance of the molecules as the Greeks conceived them. Perhaps we should be better justified in harbouring such conceptions than Democritus—but we content ourselves with certain mean values, with the gross average of velocities, with a plausible law of impact. We can manage with these, and with their aid we can calculate with all desirable accuracy the only cases of practical importance—such as the conduction of heat, or the behaviour of a gas under high pressure, or low temperature.

"A branch of human statistics—namely, life-insurance—adopts precisely the same methods. It calculates average values—mean duration of life, average death-rate, etc.—and cares nothing about the life-history of the individual policy-holders. If the insurance companies want to calculate the premium for a man of forty, they must take into consideration the probable expectation of another twenty years of life enjoyed by *all* people of forty. If the mathematician were to confine himself to taking the cases of four or five persons of his acquaintance as a basis, he might hit on a family in which it was considered good form to live at least eighty years, and his result would be useless; it would be erroneous, and the insurance company would very soon have to declare itself insolvent. Only when the mathematician takes a very large number of persons into consideration can he obtain a reliable result.

"The physicist who attempted to base a theory of gases on

the observation of a few molecules would obtain incorrect and fortuitous results—fortuitous as the Brownian movements. By *large* numbers, which constitute the secret of all statistics, chance is isolated, absorbed, and comprehended. We confine our attention to the general or common attributes of the molecules, consciously ignoring individual and accidental qualities. And owing to the inconceivably great number, the quadrillions of molecules, upon which the physicist is able to base his calculations, statistics gives him an answer which is almost certainly authentic. The element of probability, the



How an Insurance Society regards Mankind.

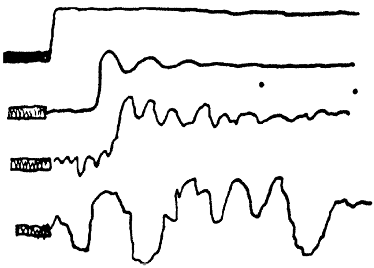
irrational, the accidental, has sunk into the boundless ocean of the myriads of molecules. It will haunt us no more."

"It will haunt us no more," said Mr. Brown in agreement. "That is good!"

Limits

"But alas—after all, it does sometimes haunt us! And then we physicists curse the Brownian movement and all its consequences. Nature trembles. You have only to look at George. But we can detect the quivering with our measuring instruments, and here the matter becomes serious. Whether we are using a torsion balance or an electrical measuring instrument, in the majority of such instruments a tiny mirror, suspended by a filament, rotates under the influence of gravitational or electrical force, and if a beam of light is allowed to fall upon it a pointer of light moves to and fro in the laboratory. In this way—for the purpose of every pointer is to magnify a movement of rotation, and so make it more perceptible (think of

the hand of a watch!)—we obtain a pointer of any length we please, which consists merely of light—that is, a pointer which weighs nothing at all. This absence of weight is an essential advantage. The less the weight of the moving part, the smaller will be the forces which the measuring instruments are able to detect. And we have really achieved wonders in the direction of delicate measurements; electric currents of a billionth of an ampere, and weights of a millionth of a gramme can today be measured with accuracy. Can we go still farther in this direction—just as far as we wish? There was a time when we should have answered, unhesitatingly: 'Yes!' But it is characteristic of the present day that we have grown more cautious. Too often has physics, in its modern developments, encountered a limit.



Measurement Curves

We have realized that a lower temperature than $-273 \cdot 16°$ C. is impossible. And today we have approached within a few hundredths of a degree of this limit. We have realized that velocities greater than the velocity of light do not occur in Nature. Here the limit has been reached—we have measured the velocity of light. We know—or think we know—that smaller bodies than electrons do not exist—and we know their size. We know the smallest electric charge that exists, and the smallest quantity of light. But the technique of measurement also encounters a limit—and this limit is prescribed for us by the Brownian movement.

Measuring instruments were devised of ever-increasing delicacy; finer and finer filaments were employed—silvered threads of quartz drawn out until they were finer than the spider's thread. And the result? These instruments were absolutely useless. The pointer, the beam of light, swung shakily to and fro. The apparatus was taken down into deep cellars, and measurements were made only at night, in order to

exclude vibration. It was no use. The cause of failure must lie elsewhere—we already know where. With their Lilliput-mirrors the physicists had descended into the world of molecules, the realm of chance, the region of the Brownian movements. Always, however carefully the mirror may be suspended, and however secluded the laboratory may be, the reflecting meter shows the oscillating Brownian movements, restlessly wavering to and fro about the zero-point, in constant, agitated motion. The molecules are merciless; the more sensitive the instrument, the greater the deflections; the more violent the 'thermodynamic oscillations,' the more completely are the tiny deflections which we are seeking to measure—due, for example, to an electric current—swamped by these constant movements about the zero-point. With our measurements too, then, we have reached the limit set by Nature. Smaller amounts of energy cannot be measured—and with that we must be content. The Brownian movement is to blame."

The old man shrinks into his chair and bows his head in embarrassment. What strange things he has to hear!—But there are better to follow.

"That is only one aspect of the matter. The other is this: In the realm of the molecules, do the laws of our physics still apply? Apparently not. To give only one example—consider the problem of temperature. At a temperature of 25° the average velocity of the molecules is 500 metres per second. If we had a single molecule with this velocity, what temperature ought we to attribute to it? 25°? Perhaps. But in a gas at − 50° there are still molecules—they are numerous enough, indeed—which have a velocity of 500 metres per second. And if our molecule came from a container filled with gas at this temperature, should we not have to call it 'a hot − 50° molecule?' Or is it perhaps a very slow molecule from a container filled with gas at a temperature of 500° ? There is nothing to tell us which container it comes from. Evidently it would be better to express no opinion on the matter. The notion of 'temperature' has meaning only when we are dealing with a very large number of molecules, which have a definite *mean* velocity. A single molecule can have no temperature at all—any more than a mathematical proposition can be red or

green, or a motor-bus have a religion. It is well to proceed with a certain caution on descending into the microcosm of the molecule. We must not be surprised if certain notions which we have brought with us from the great world lose their meaning there, much as our European customs would lose their meaning under the absolutely different conditions obtaining in Papua. Modern physics has discovered still other and far more important reasons for this. Yes, you've caused us a lot of trouble, Mr. Brown. But now listen to the final consequence."

The Death of the Universe

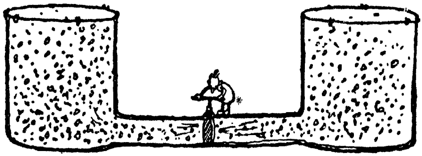
"Nature's preference for uniformity seems inevitably drifting toward a grey and desolate end. A continual degradation of energy is proceeding, for although theoretical physics is acquainted with reversible processes—which occur without 'losses,' without friction, to all eternity—Nature knows nothing of them. A portion of the energy available is always lost, a necessary duty paid to the surrounding Universe. It is transformed into heat, and heats a lamp, or the tyre of a car. A difference of temperature would still exist, and from this difference, in accordance with the second fundamental proposition, the energy can be won again—though only part of it. But this, too, will quickly reach equalization; the heat flows into the water, into the ground, and leaks into the surrounding world. The energy, of course, has not vanished from the Universe—it persists in the heat motion of the molecules—but it has withdrawn itself out of reach. Further, it seems even to have withdrawn out of reach of Nature.

"The objection has been made that according to kinetic theory a circumvention of the second fundamental proposition seems possible. If two vessels are connected, and if the connecting passage is closed by a door, and if a highly intelligent little creature, a 'demon'—his father was the famous Clerk Maxwell—is installed as doorkeeper, he will be in a position to snap his fingers at this second proposition. He has only to open the door whenever a swift molecule approaches, and quickly close it when a slow one comes trundling along. In this way

he would gradually collect all the swift molecules on one side of the door, and all the slow ones on the other. He would effect a segregation of velocities, and obtain a serviceable difference of temperature capable of doing work.

"We shrug our shoulders and dismiss the objection. The theory was not devised for demons. Was it correct? So far we have not been able to demonstrate the existence of Maxwell demons in Nature. At the best, they are thinly scattered in the Universe. There are too few of them to influence the world-process. Irresistibly, entropy increases.

"Scientists have spoken of the death of the Earth through cold. Far more desolate, far more inevitable seems the 'heat



death' of the Universe. Everywhere are processes which squander energy and increase entropy; at most there a few in which it is conserved; but nowhere, however far one seeks, is there a gain of energy. Must it be so? Is the universe running down like a forgotten clock? Will it drown in heat? One sheer dead ocean of molecules, in sterile, unthinking zigzag movement. Nothing but a dead level of equalization. Nothing but grey uniformity, far as the eye can reach. Is this desolate picture the true conception of our future? To sink into a warm, indefinite nebula—will that be the end of the world?

"To be sure, these are speculations. It is perhaps questionable whether we are justified in applying the principle of entropy to the Universe as a whole—for as you know, it is always well to be cautious when one transcends the limits of the realm of experience. What do you think, Mr. Brown?—Hullo! . . ."

The chair is empty. Our amiable visitor has disappeared. And as I look into the microscope I see only a confusion of dancing particles of dust in lively Brownian motion—but not

a trace of George. Only a faint scent of lavender still lingers in the room.

Well, as I told you just now, it is an incredible story.

Why are the Atoms so Small?

Can we explain why there are so many molecules in a gas—why the atoms and molecules are so small? Could we not imagine atoms a thousand, a million times larger? At first sight the notion does not seem to present any special difficulty. Nevertheless, the idea is hardly permissible.

Let us follow an argument of Schrödinger's.—An engineer who is building a bridge or a power station will allow for a certain margin of safety. The bridge is not built just so strongly that a train can cross it only at considerable risk; it will be of such proportions that two trains can cross it at the same time. The engineer will have to consider the wind-pressure and the weight of the snow in winter, and finally he will "add a bit on"; he will make the bridge a little stronger than is apparently necessary, so that it will be equal to unforeseen mishaps. In short, he will endeavour to keep all his measurements in excess of the level of loads and disturbances. So, too, the radio transmitter, if it is to be plainly audible, must keep above the general level of disturbances—the constant buzzing in the receiver, the crackling and crashing which give warning of the electrical activities in the atmosphere. (In summer the Earth is more "alive," the atmosphere is noisier, the level of disturbance lies higher, and weak transmitters are submerged as rocks in the bed of the river are submerged at high tides.) One may say that in a certain sense the whole world represents a level of disturbance. The constant, uncontrollable oscillatory movements of the molecules swallow up anything that falls into them. Any measuring apparatus, any mechanism, must evidently operate far above this level of disturbance—if it is to work at all; if it is to yield, not an uncontrollable buzzing, the result of chance disturbances, but a disciplined music.

An engineer who designed such a complicated mechanism as a man would thus have to remove him from the region of the

Brownian oscillations. He would make him big enough to obtain exact and reliable statistics, for only if the man were sufficiently large would the individual influences of the molecules be negligible. Otherwise the result would be a quivering creature like the unfortunate, microscopic George, sensitive to the impacts of single molecules, and thrown continually to and fro. Further, not only would the micro-man be tossed about the world as a whole, so that he might suddenly, without realizing what was happening to him, find himself translated into the next room; or as he was going to his office in the morning, an unfortunate constellation of molecules might suddenly land him in a public-house or speak-easy! Worse still—his internal economy would be in constant movement. He might be sitting in consultation with a financial magnate: a molecule would strike him just under the kneecap, the involuntary and inevitable reflex would throw the leg forward, and deal the financier a violent kick under the chin.

But even worse things would happen. All the vital functions, all the mental processes would be subject in an appalling degree to "thermodynamic fluctuations." Whatever theories one may hold as to the processes of thought, at all events the purely material apparatus of the brain plays its part in them, and we may doubt if anyone could think rationally with or by means of a mechanism which was in a state of constant and uncontrollable disturbance. We upbraid our "crude senses," says Schrödinger, because such an impassable gulf divides them from the "interesting" world of the atoms; because we cannot actually see the atoms. We ought rather to thank the Creator for this state of affairs—for it is very doubtful whether we could see at all if our eyes were a few thousand times smaller! At any rate, it seems to be a most sensible arrangement that the atoms should be so small in relation to ourselves, and that we should consist of so many atoms.

PART TWO

ELECTRICITY

ELECTRICITY

A Talk about Thunderstorms

SUDDENLY the light went out. For a moment a descending flash of lightning lit the dark room with a harsh, bluish radiance, and almost simultaneously there was a crash of thunder that made the windows rattle. Then the room relapsed into the blackness of night, and the loud plashing of rain was heard

as the raging wind flung the torrential downpour against the house. "A pretty business!" said the master of the house. "The light's failed again. Now you are a physicist—you ought to be able to explain why this happens."—"Are the fuses intact?"—Yes, they were intact, so there must have been trouble at the power-station, or perhaps the lightning had struck the cables. Candles? No, there were none in the house; there ought to be a lamp somewhere downstairs, but there certainly wasn't any oil.—"After all," I ventured to say, "it's quite pleasant for once to sit in the dark; here we are, in shelter, looking out on the storm. And outside the Almighty is lighting the world from His own power-station!"

"Will it one day be possible to capture these enormous quantities of celestial electricity?" asked the youngest son. "What's the use of you physicists if you can't do a thing like that?"

"Gently, gently!" I said; but a dazzling flash almost took our breath away.—"You see," I continued, "you all think that Nature has a tremendous supply of electricity out yonder. It's true that millions of volts and thousands of amperes are raging overhead—currents a thousand times more powerful than that of our damaged cable. But how long do they last? A fraction of a second. You are a merchant—how much would you give for a thunderstorm? 1 thunderstorm, with 200 flashes, first quality, extra loud thunder, sheet-lightning gratis. Well . . .?"

"Well, it wouldn't be cheap. Let us say . . . well . . ."

"No, save yourself the trouble! You can have it at cost price. Sixpence!—One moment; let me explain. One ordinary bell-battery generates as much electricity, during its lifetime, as the storm out there. Of course, the thunderstorm isn't as modest and industrious as a bell-battery, and it knows a good deal more about effective display. Nevertheless, the total current is about the same."

A storm of disapproval and derision descended upon my head, hardly less violent than the storm outside. My assertion was ridiculous and absurd; either I knew nothing about physics or the whole science of physics knew nothing about its subject. I attempted to defend myself.—"I should like to ask you a few questions, if I may, so that I shall at least know what I am accused of. Now—a thunderstorm generates more electricity than a bell-battery—is that it? Well, we must first of all decide what a quantity of electricity means; but before that may I ask you—what is a thunderstorm?"—"Why, electricity, of course."—"What? Is the thunder electricity?" —"No, of course not—the lightning! The thunder is just a noise, a detonation, which is caused by the lightning."—"And I have always imagined that I could see the lightning, while everyone knows that electricity is invisible!"

"Hold on, now!"—It was the master of the house who spoke. He had quietly switched on a pocket flash-lamp, and

going to the bookcase he took out a little dictionary. "Lightning-flash, an electric spark."

"Good. I grant you that. But a spark isn't electricity. Now look here—we'll say that a perfect stranger, perhaps an Eskimo, or someone from a remote and forgotten farm in the mountains, came into these parts and entered a little country tavern, where they sold an excellent local wine. He saw a jolly company sitting round a table, laughing and singing; and he sat down beside the landlord, and asked him why his guests were in such high spirits; and the landlord lifted his glass, and replied: 'That's what good alcohol does, that is.' And the man went his way until he came to a village, and there again he went into an inn. The day before there had been a terrific row there, and the piles of broken chairs and tables, and the shattered glasses were still lying in the puddles on the floor. It was not at all a pretty picture, and the stranger was horrified when he heard one old woman say to another: 'Yes, yes, that's what alcohol does, that is.'

"I don't know what became of the wanderer—whether he went quietly back to his mountain village, taking the riddle with him, or whether he asked some intelligent person what alcohol really was.

"One must never confuse the effect with the cause. And we at least needn't go back to the mountains. To be sure, if you ask me: 'What is electricity?' I shall tell you frankly—I don't know. But we do know quite a number of things about it—so many, that it is well worth your while to listen to some of them. They say that we moderns have forgotten how to wonder. Perhaps we have only forgotten how to reflect.

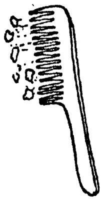
"We press a switch, and the room is flooded with light. We press another, and a gentle heat is radiated. We have underground railways, trams, street-cars, workshops—all electric. The neon and mercury-vapour lamps shine red and blue on the housetops, and are reflected from the wet asphalt pavement.

"The oldest electrical experiment was made by the Greeks, with a piece of amber (Latin *electrum*, Greek *elektron*, amber). Anyone who possesses an amber necklace can repeat this experiment forthwith; he has only to rub the amber vigorously

with a cloth or scrap of fur, and he will find that as a result of the mere friction the amber is in a very peculiar condition. In human beings, too, there are such conditions; you find people who are highly excitable, who fall out with their neighbours; we call them hysterical. In the case of the necklace we say that the amber is 'electrified.' "

"But I have no amber necklace," interposed one of the ladies."

"Those who have no amber necklace need not despair—unless they happen to be bald. Here is a household recipe for electricity: Comb your hair quickly and vigorously—preferably when it is freshly washed and well dried—with a dry, non-greasy comb. The comb is then electrified—and if you hold it close to a number of tiny scraps of paper you will see that it exerts a remarkable power of attraction. The scraps of paper become restless; a few irresolute movements, and with a sudden jump they fly up to the comb—through the air, and against the force of gravity, and against all reason. That's the whole experiment!"



"Simple enough!"

"Simple though it is, the essence of the matter is in it. Of course, the comb was not the only thing affected. If you were on the alert—and I hope you were—you will have noticed that your hair lifted on your head, while you felt a curious tingling in your scalp, and heard a faint crackling; if the room was dark you may even have seen a few tiny sparks. That's all for the present." And I leaned contentedly back in my chair.

"Really! So that's all! You surely don't imagine that you've explained anything? For example, the thunderstorm out there? What has the comb to do with it?"

"It was electrified . . ."

"Electrified—that's only a modern and rather pompous name for something unknown. Besides, your assertion is only partly correct. The comb *attracts* little bits of paper, and does other such magical tricks, because it's electrified. Was the hair electrified too?"—"Yes, of course." —"But the hairs tried to stand on end—they apparently repelled one another. Perhaps *that* was because they were electrified, eh?" And now it was

the master of the house who leant back with an air of satisfaction.

I had to give in and beat a retreat: "We will agree that there is in this Universe something that we call electricity; a substance, a condition, or what not. We will even assume that there are two kinds of electricity, so that we can explain the different behaviour of the comb and the hair. But I will take advantage of the darkness, and the fact that you can't do anything more intelligent, and tell you something—only a little —more. The Greeks, as I have said, were familiar with the amber experiment. The first to repeat it in modern times was the Englishman Gilbert, in the sixteenth century, and he showed that not only amber, but a number of other substances can be electrified. Otto von Guericke built the first electrical machine, and made the discovery of electrical repulsion. That was about 1666. Just two hundred years ago, in 1734, Du Fay found that there were two kinds of electricity: people called them positive and negative, two entirely arbitrary descriptions. And every electrification, as Franklin discovered in 1747, is simply a separation of the two kinds of electricity. In 1785 Coulomb enunciated the law in accordance with which the two electricities influence one another. But the question still remains to be answered: Is the electrification merely a condition of the comb, a quality like any other, such as blackness or heaviness or elasticity, or is it something more? In other words, is there such a thing as pure electricity? What do you think?" —"Why, of course, there must be!"—"No. Don't forget that we are now in the twentieth century, and must consider things from this standpoint. The scientists believed for a long time that heat also was a substance, which could flow from one body to another; a subtle, gaseous substance. Today we know that this is not the case—that heat is only a *condition* of bodies. Molecular movement. But electricity is another thing."

The Basic Experiment

"About 1870 Hittorf, Crookes, and others at last succeeded in discovering pure electricity: it had hidden itself in almost completely exhausted glass tubes—vacuum or Geissler tubes,

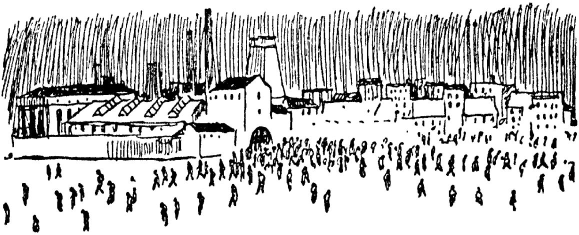
they were called. For example, if you pump the gas out of a Neon tube and send an electric current through it, if the pressure of the gas is very low indeed—equal to the weight of a thousandth of a millimetre of mercury, or about one-millionth of the ordinary atmospheric pressure—the glass opposite the negative pole, the 'cathode,' glows with a bright green light; it becomes 'fluorescent.' It was found that rays proceeded in straight lines, perpendicular to the cathode—'cathode rays'—which consisted of little particles that rushed through the tube with very great velocity, and where they struck the glass they created the bright fluorescence."—"And how does one know that they fly in straight lines?"—"If you fix a bit of tin in their path they can't penetrate it, and a sharp shadow is cast on the end of the tube.

"The lightest substance we know of in the Universe is hydrogen; one of its atoms weighs 0·000,000,000,000,000,000,000,000,663 of a gramme. But when the scientists determined the mass of the cathode rays they found, to their amazement, that these swiftly flying particles are something like 1,840 times lighter than a hydrogen-atom. In the ordinary sense of the word, they don't weigh anything at all."

"But you said just now that hydrogen is the lightest substance?"

"Yes, so it is. The cathode rays couldn't be a substance in the ordinary sense of the word; they couldn't be a chemical element or a chemical compound—they were *pure* electricity. With these rays Hittorf had discovered what had been sought for so long—electricity itself. Stoney proposed that such a particle should be called an 'electron.' The electron is the smallest particle of pure electricity conceivable—an electric atom. Millikan has even succeeded in directly measuring its charge, and he was able to prove that smaller units of charge than the charge of electron, the 'elementary electrical quantum,' do not exist in Nature. It was negative electricity that was thus discovered. The swarm of electrons which is shot out of the cathode, like hands leaving a factory at closing-time, is an electric current. In each case there is a great repulsion, and the immediate goal beckons in the distance—a hot supper, or the positive pole, as the case may be.

"Is there also such a thing as an independent positive charge? The question was bound to be asked. In 1876 Goldstein, after many experiments with Geissler tubes, discovered the bearers of positive electricity in the 'channel-rays'—so called because they were made to shoot through little openings, or channels, in the cathode. The 'channel-rays' were positively charged; but however the experiment was varied, no one ever observed a channel-ray lighter than the nucleus of a hydrogen-atom. And in the textbooks of physics you will find this sentence in italics: *Positive electricity has not hitherto been observed in a pure state. It is always bound up with matter.* The unit of



positive charge is called a *proton.* So we have two elementary electrical particles, whose *charges* are opposite but equal, but whose *weights* are different—as 1 : 1,840.

"This was the official view until the year 1932. In that year Anderson, in Chicago, discovered the positive electron—a positively charged elementary particle, whose weight was to that of the proton the same as that of the electron—1 : 1,840. At first no one would believe him. At the present time no one doubts the truth of his discovery. There are positive electrons, too—*positrons*—pure positive electricity, free from matter, as the truly heretical and attractive new theory of an Englishman, Dirac, required."

"And what did you do with your text-book? Throw it away?"

"I have crossed out the word *always* with red ink, and written *most frequently.* So the sentence is still correct."

"Aha! So that's how the case stands now. Electricity is a sort of substance"... "A non-material substance!" I interrupted...

"which exists in tiny particles. There are two kinds: negative electricity, whose units, the electrons, can wander about freely; and positive electricity, which is almost always inextricably bound up with matter. It is only rarely that we find positive electrons which do not need matter to support them!"—"Quite so. But there's no getting over the fact that this doesn't explain what electricity *is*. We have only ascertained the form in which this something occurs in Nature. In itself, the existence of a negative or positive electron remains a miracle. We'll call it miracle Number One. And now let us see how far we have got with our definitions. Like is unwilling to join with like—two electrons repel each other as two jealous human beings do. They can't bear one another. But this hatred makes the love of an electron and a positive charge all the greater. And this explains everything. When we comb our hair or rub a stick of sealing-wax with a scrap of fur the happy union, plus-minus, which existed in both materials, is destroyed by the rapid movement—dissolved by higher authority. There's a parting after years of friendship. And for some reason which is still hidden from us, the electrons prefer to take refuge on the comb: it pleases them better. They collect there in great numbers, leaving their positive partners, lonely and charged, on the hair. Comb and hair have become electrified!"

"You know, that sounds very simple. People are often tempted to look down with a pitying smile on the generations of inquirers who probed into the secrets of electricity and failed to unravel them."

"Yes, of course, it's quite simple. But don't forget that it is much easier to sum up the labour of centuries in a few phrases than to drive knowledge one tiny step farther. And don't be in a hurry—there are plenty of surprises to come. . . . We were talking about friction. We comb our hair—and nothing seems to have happened. But when we take out the comb, and physical contact ceases, the catastrophe is apparent. It is horribly uncomfortable on the little comb for this crowd of electrons; but it's too late to do anything about it. There they are, all sitting together, a mob of deadly enemies. They can't get back; they can't get up and go; and they long to return to their partners, who are left on the hair. So intense

is their longing that its manifestation is almost corporeal. Like a thin thread of elastic this longing reaches out through space—as though the soul of this friendship were stretched on the rack. To this desperate, almost tangible longing we give a matter-of-fact name: we call it a line of force.—And this is the second mystery.

"Like a subtle, flexible, eddying thread of smoke this attraction passes through the ether—a thread which has at one end a negative electron, and at the other a positive charge. Rather like this."

And I take the pipe from my mouth, and blow a fine round smoke-ring. It is fortunate that I am an expert in the art of blowing smoke-rings; I am even rather conceited about it. And it is really worth while to consider these curious formations.

Slowly they drift through the room, their component particles holding closely together, and one sees how quickly and diligently they whirl round the ring. Then, at one point, they become condensed; this portion of the ring stops, while the rest travels slowly on, driven by the draught from the window, drifting in longer and longer wisps, now straight, now tangled—but each thread stretches and lengthens, yet holds tenaciously together, until it passes out of sight.

"Yes—but what was I going to say?—the similarity between an electric line of force and a row of smoke-rings is astonishing, and it goes deeper than you would think. And two smoke-rings won't mingle; they would rather bend, avoid each other, and repel each other; and in the same way two lines of force repel one another. There is a pull along the lines of force, just as there is a pull along a thread of elastic; the separated charges want to rejoin one another; here is the 'longing' of which I spoke. But across the lines there is *pressure*—they try to avoid

one another. That is why your hair stands on end when you comb it—the cross-pressure of the field pushes the hairs apart."

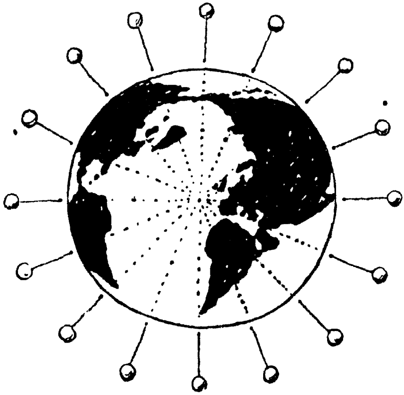
"Just a moment, now," cried the son of the house. "I think you yourself are sinning against the sacred spirit of lucidity. You have been speaking of lines of force, but you haven't said a word about a *field*. I, at all events, don't know what you mean by it; I have never come across such a thing as a field."

"A field? Oh, yes, you have—who hasn't? You go into a room where you expect to find a number of people—a jolly gathering, perhaps, or a group of bored and apathetic persons —and even as you stand at the door you are overcome by a sudden feeling, a startled premonition; the moment you enter the room you are almost physically aware of it—a curious tension lies over the company. It may be a great assembly, or just a small scratch gathering, and no one takes any notice of your arrival, unless here and there someone looks round at you with a half-impatient, half-hostile turn of the head. What is happening—whether two opponents are longing to fly at each other's throats, or whether those present are threatened with a common disaster—you haven't the least idea. Individually, these people look ordinary enough; there is nothing special to be noted about them; at all events, at a first glance. But there's no doubt about one thing: the tremendous intensity, the curiously imminent and oppressive premonition that fills the room and is weighing on all the people. You yourself can't hold aloof from it. You know that now something is going to happen, and is going to happen soon. But the critical moment hasn't come.

"It may seem strange that it is only at such rare moments, far removed from the sphere of rational comprehension, that we human beings are aware of this state of tension, this impalpable fluid, with a super-rational and momentous certainty. One may call it a 'field,' to use the scientific term. Something is different about the room; the atmosphere is 'charged'; one experiences a sense of stored-up energy; and perhaps this comparison is scientifically justified."

The Field

"The notion of the *field* is a fundamental concept of modern physics. We live all our brief days in a 'field,' which we do not notice merely because we are accustomed to living in it. All round about us space is in a peculiar condition, which we call normal simply because we are accustomed to it. We take a ball, hold it in the air, and let it drop—and of its own accord,

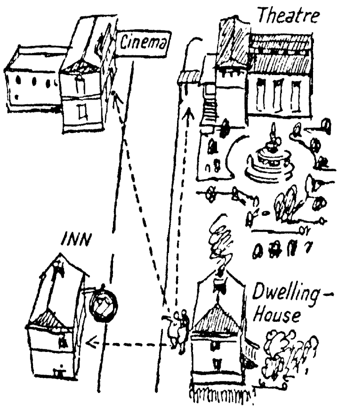


impelled by an irresistible force, it begins to fall to the ground, first slowly, and then with increasing velocity. Why doesn't it remain hanging in the air—why does it move at all?—Because it finds itself in the gravitational field of our planet, and whether it likes or not it must obey the urge of the field, and its inner tension, and fall as far as it can. That is a matter of course, you think? But no: if one were to leave this same ball quite alone in the middle of the Universe, and think all the stars away, it would remain comfortably and contentedly in its own place—for there would be no reason why it should move. Here I am, it would say, and here I remain.

"The lines of the Earth's gravitational field are easily found —they run at right angles to the surface of the globe. You could man a legion of Piccard's stratosphere-balloons, and let them ascend until the skies were darkened by them, and if

you let a long, weighted cord hang down from each of them, these cords, following the pull of the weights, would represent the lines of the field. We should then have a picture of our gravitational field. And now you understand what the lines of force are: they show the direction of the force at any point of space. It is in this direction that any body which is subjected to the force will move; every heavy body falls along such a line.

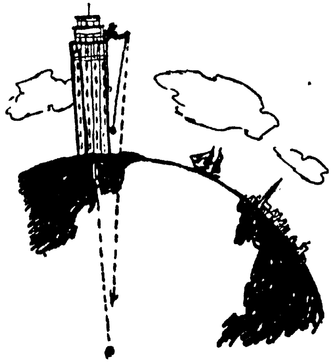
"We know why the ball falls: it is attracted by the Earth, and moves toward the Earth's centre. All bodies have weight—and so they all attract one another mutually. While the ball falls towards the Earth, the whole Earth 'falls' an infinitesimal distance towards the ball. But there is still more to follow:



"It seems a matter of course to us today that the gravitational lines of the Earth should reach out into infinity—and that the attractive force of the Earth, although it grows weaker and weaker, should never absolutely cease, no matter what the distance. In the old days people believed that the region of gravity was wrapped all round the Earth like a thin veil of smoke, and a Jesuit Father even attempted to fire a cannon-ball through and beyond this layer of attraction. Such an attempt could be successful only if the cannon-ball had an initial velocity of 11 kilometres—nearly 7 miles—per second; then, although strictly speaking it could never escape from the Earth's gravitational field, it would nevertheless have enough momentum to overcome the ever-diminishing attractive force of the Earth. It is also obvious that on the Moon one would be mainly conscious of the gravitational field of the Moon. Nevertheless, the field of the Earth would exert a considerable

influence there; for even we, on the Earth, have daily evidence of the palpable influence of the much smaller field of the Moon: the vast masses of water which encompass the Earth, in constant alternation of ebb and flow, are compelled to make their gigantic movements by the attractive force of the Moon.

"When the Joneses' Uncle George comes from Cardiff to pay them a visit, there is always a tremendous dispute every evening as to where they shall go. Jones wants to take Uncle George to his favourite pub, just the other side of the road; but his wife, who is more for culture, insists on going to the theatre, at the end of the street. In the end they all agree upon a middle course—they will go to the cinema, on the opposite side of the street to the theatre.—Well, something like this happens when two forces are at work in different directions. This time we will drop the ball from the top of the Woolworth Building in New York. If the ball and the building were alone in space the ball would move towards the building. But the Earth is there, and the Earth says: Come along with you, towards my centre of gravity! And in the end they agree upon an intermediate course; and this has been actually demonstrated by accurate scientific experiments with falling bodies. The ball does not strike the ground exactly 'under' the point from which it was dropped, but just a little nearer the building."

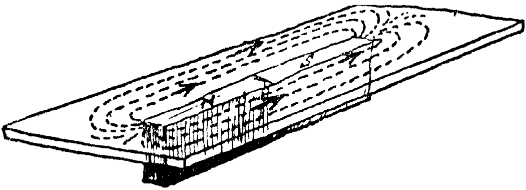


"Splendid—I'll make the experiment tomorrow!" says the eldest son.

"Well, why not? But the deviation will be infinitesimal, because the Earth is so much heavier than the house. Even two great armoured cruisers, with their enormous masses, attract each other, at a distance of one metre, with a force

of only one milligramme. Still, in principle your experiment would be in order. It would give a more definite result if the building were replaced by a mountain. The lines of force would then bend towards the mountain; they would be distorted by it. And a free body would always fall along these lines.

"There is a second sort of field in this world of ours—a field which I expect we thought remarkable enough in our childhood: the *magnetic field.* I remember very well how astonished I was, as a little boy, by the miracle of the compass, and how again and again I incredulously tested it to see whether the little blue steel needle did really always point to the North.



'Why does it?' I wanted to know.—'It's a magnetic needle,' I was told; 'it always points to the magnetic pole of the Earth.' And with that I had to be content.—In order to make the actual physical phenomenon more plainly visible, let us lay an ordinary bar-magnet on the table. It is a bar of steel, the size of a carpenter's pencil, and one end, the 'north end,' is painted red. There it lies, doing its best to look as innocent as possible. But its field surrounds it invisibly.

"We will make the old schoolboy experiment. A sheet of paper is laid over the magnet; a pinch of iron filings is poured on to it, and then the paper is gently tapped. As though of their own accord, following an irresistible urge, the filings arrange themselves in the familiar lines. A small magnetic needle—for example, a magnetized gramophone-needle—if we lay it anywhere on the paper, will place itself in the direction of the lines of force.

"These are the lines of the magnet's *field.* For this magnet, innocent as it looks, has by its mere presence influenced and

transformed the space around it. It has thrown the space in its neighbourhood into a peculiar state of tension; we speak of a 'magnetic field.' Wherever the magnet may be, it is surrounded by a field; the space around it is charged with this peculiar state of tension, which is not visible to our eyes, but which betrays itself at once if we gently brush the iron filings or the gramophone-needle. Wherever we take the magnet, it carries its field about with it, just as a great man carries the influence of his personality about with him.

"Then there is a second familiar experiment: A stick of sealing-wax is rubbed with fur (or we could even have taken the comb of which we were speaking), and is laid on the table and covered with a sheet of paper. The paper is sprinkled with plaster of Paris, and tapped—and the white powder arranges itself in lines of force. We know that sealing-wax is electrified by friction; and now we see that an electric field is generated around it. So electrically charged bodies modify the space around them, invisibly and mysteriously, like the magnet. The sealing-wax, too, takes the field with it when it is moved. And if the sealing-wax is taken away you can shake and tap the white powder as long as you like—it will make no attempt to arrange itself in a pattern. With the removal of the sealing-wax the space that surrounded it has reverted to its old, tensionless, neutral condition. It is as though two game-cocks had suddenly disappeared from a political meeting—and with their departure the tension in the room is relaxed, and the people begin to chatter about harmless, indifferent subjects. The field collapsed with the disappearance of its cause.

"So this—to repeat it again—is the concept of the field: In a field, whether electric, magnetic, or gravitational, there is a special state of tension at every point of the space surrounding the exciting body. At every point of the field a force of definite direction and magnitude acts upon a body subject to its influence. A body free to move in the field will move in obedience to the force acting at that point of the field at which the body is situated. We can represent the field by lines of force if at every point of it we draw the direction of the force. We shall then find that a free body moves in the field along a line of force. It is just as though the line of force were a narrow tube,

through which a spherical body could roll, but from which it could not escape.

"What is meant by 'a body subject to its influence'? That is soon explained: in the gravitational field, a body having weight; in the magnetic field, a magnetic body; in the electric field, an electrified body. In short, it must give the forces of the field some hold upon it. If Uncle George, for example, were approached by a somewhat hectic-looking youth in a black slouch hat, who invited him to a lecture on eurhythmics, or a discussion of the poetry of T. S. Eliot, the good man would only stare at him; his behaviour would not be influenced in the least by this uninfluential person. Similarly, a non-magnetic body will pay not the least attention to a magnetic field—as you will see at once if you replace the steel gramophone-needle by a fibre stylus."

Transmitted and Remote Action

"Michael Faraday, who from being a bookbinder's apprentice became a professor of physics, and President of the Royal Institution in London—Michael Faraday was the man to whom this bold conception first occurred—it was he who first ventured to advance the theory of the field. He was an experimenter and a tireless investigator; but this brilliant intuition led him far beyond the range of his experiments, and indeed far beyond the thought of his own times. Like a flash of lightning, with almost painful lucidity, the knowledge must have come to him. It was one of the great moments of human history. Faraday may have fought against his own conception; it may have seemed to him intolerable and senseless. But here was a man of a glorious freedom of intellect; for Faraday was no academic thinker. He came to science in obedience to an inner compulsion, and he followed untrodden paths. Therein lay his strength. It must have been easy for him to believe in his intuitions—easier than his contemporaries found it. Not until fifty years later—actually in our own time—were the full power and profundity of his ideas made manifest.

"Newton had explained the movements of the heavenly bodies by his wonderfully simple mathematical law: The force of attraction between two massive bodies is dependent only on their mass, and their distance. But he said nothing as to the nature of this force. Two bodies act upon one another across an interval of empty space; *how* they do it is their affair. A miracle? Very well; we accept the miracle and build our theories upon it. And it explains for us all the data of observation, the movements of the planets, the eclipses of the Sun and Moon. We can rely on the miracle. It is a punctual, respectable, disciplined miracle.

"Nevertheless, it did not satisfy Faraday. He made further inquiries—he inquired into the anatomy of the miracle. And it seemed to him a matter of course that two bodies couldn't, so to speak, get round and push one another from behind; they must attract one another *through* space, and space must surely know something about it. And once more it was shown that the too early abandonment of an inquiry is an obstacle to knowledge. Humility is good, but premature modesty does not lead to understanding.

"Newton's law of gravitation was regarded as the ideal pattern of a scientific description of natural fact. Coulomb discovered the law conditioning the mutual interaction of electrically charged bodies. And it was both mysterious and convincing that this law should be—Newton's law of gravitation! The mathematical form of the two laws is precisely the same. The force exerted between two bodies depends only on their electrical charge and their distance.

"The force of attraction between the sun and the planets is able to bridge empty space; but the electrical forces of attraction also are able to act across empty space. All our electrical experiments could be carried out under a glass dome from which the air had been exhausted; apart from very minute, barely measurable deviations they would yield precisely the same results.

"But it is in this empty space that the field is generated and maintained. And for Faraday the field was something physically actual, something real, and indeed the only fundamental thing. The field alone is important; the charges are significant

only in so far as they build up the field, throwing nothingness into that peculiar state of tension. It called for unimaginable courage thus to liberate electricity from the fetters of matter, and translate it into empty space. But this courage was wonderfully justified by the nature of electricity. To Newton also the idea of the field had occurred; to him also it seemed attractive —but he ventured no farther. The path seemed too mysterious.

"When we speak of the ether we are really only building an intellectual bridge. The ether is supposed to be a medium, a free, immaterial something, which penetrates all substances, and in which the field is located. An electric or magnetic field signifies a state of tension in the ether. Everywhere, even where there is 'nothing,' there is still ether. Whatever we are really to think of the ether—and to some its very existence is rather questionable today, while others prefer not to speak of it at all—for the time being we will accept the hypothesis of the ether; it is useful, and a 'comfortable word.' "

"Very well—why shouldn't we let the ether exist? And is that all there is to it?"

"I should have liked to say a little more about the field. We have a very good idea of what we should call 'strength of field'—intensity of field. Wherever the lines of force are huddled close together—that is, where there are a great many of them to the square centimetre—the force acting on a body is also great. You will remember that we compared the lines of the field to stretched threads of elastic.

"The second notion that we must bear in mind is that of *tension.* I'm sorry, but again I can't think of any better illustration than these threads of elastic—and with that I've said really all I need to say. Just as you have to do a certain amount of work in order to stretch an elastic thread, so you would have to do a certain amount of work if you could cautiously take a negative and a positive charge between your fingertips and pull them apart. The greater the work, the greater the tension. Also, conversely, this work exists—invisibly—in the field. We may say that it takes a certain amount of work to pull the two charges apart against their force of attraction. We can also say that it takes a certain amount of work to separate the two charges because in so doing we have to throw the whole

of the surrounding ether into this peculiar state of tension. And so Faraday declared."

"There's one question I've had on my mind for a long time," interposed the master of the house. "It's about these lines of force. What is there *between* two lines of force?"

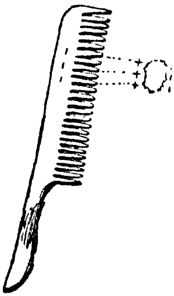
"Well, now, I'm sorry already that I let you ask that question —for I can't really answer it. We can take the view that a single line of force actually represents a real *something*—that its head consists of a positive charge and its tail of an electron. Then the field would actually be like a fabric of parallel lines of force, with vacant interstices; and we think this state of tension exists *everywhere* in space only because the number of electrons is so enormous. This is the view of Philip Lenard, the celebrated physicist of Heidelberg. There is a good deal in its favour, though it can hardly be distinguished, experimentally —owing to the density of the structure—from the second conception: That the ether is really in tension *everywhere*; so that we can't speak of interstices at all. It is continuous. This view seems better adapted to the conception of the field —and one thing, above all, is in its favour: the mathematical method devised by the great English physicist, Clerk Maxwell, which is employed in 'field physics,' does not allow for separated lines of force; Maxwell's field-equations require a continuous field. And there are few things in physics that attain to the perfection of Maxwell's equations—their classic precision and elegance, their almost uncanny profundity. A whole universe lies contained within four lines. The formulae seem to know more, to lead farther than we suspect; to live a life of their own, obedient to their own laws, which are not ours. Mathematics is a clever science; it often knows more than its discoverers.

"But we had better return to our subject.

"We have combed our hair and removed the comb, and we have held it near some scraps of paper. The yearning between the positive and negative charge, the system of lines of force, passes through the intervening space.

"Now comes the experimenter. Let us suppose that a positive charge appears on the scene. It immediately puts forth a line of force, and amiably offers itself: Here I am! And now

the moral unreliability of the electron becomes apparent. *You* are positive, we'll say; you are sympathetic. The distant, rightful partner is forgotten. All the electron's friendship is now for the newcomer—and the positive charge, following the pull of the electron on the comb, begins to rush along the line of force and into its arms.



"But even if the body experimented is unelectric or dielectric, like our scrap of paper, it can become electrified. By the pull of the lines of force the alliances in the paper are disturbed, the positive charges are drawn in the direction of the field, while the negative charges want to have nothing to do with it, and avoid as far as possible the neighbourhood of other electrons. The result is a separation of the charges; the force of attraction wins the upper hand, and the apparently unelectrified body moves along the lines of force. There is no magic about it—beyond the fact that electricity exists, and that plus and minus attract each other. That, of course, is inexplicable—and will quite possibly remain so. We cannot overstep the limits of our knowledge."

Conductors and Non-Conductors

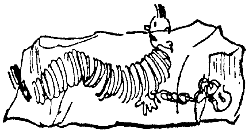
"The separation of the charges in the scrap of paper was, of course, incomplete. In a metallic object it would have been complete.

"What are metals? Amoral institutions, from our point of view; for in the metals all the bonds of discipline and order are abrogated; in them the electrons can rush about at liberty, and almost without obstruction can fling themselves into their neighbours' arms. No wonder the metals occupy a special place in electrical theory!

"In an electrical conductor—a metal—the electricity is more or less free to move. In non-conductors—insulating substances like amber, glass, porcelain, etc.—it is tied down to its place.

"And now we can begin to understand some kinds of electrical apparatus. Here, for example, is a condenser: Two islands, separated by an impassable channel. On the one island a whole horde of men has been concentrated; on the other there are only women. They cannot join one another—the water is much too deep. But even though the couples cannot come together, longing has its way with them, and the mutual repulsion and the inconveniences of the overcrowded island are endured as cheerfully as possible.

"Electrically speaking, a condenser consists of two opposing surfaces of metal, on which electric charges can be collected (or condensed), because the reciprocal attraction across the dividing gulf annuls the repulsion.



Capacity is the relative power of holding, the ratio of the amount of electricity held captive to the tension that arises. A good condenser—that is, a condenser of large capacity—can therefore hold a great deal of electricity even at a low tension, for it is, of course, the tension, the field that comes into being, that makes condensation possible. (In the same way, one could speak of our two islands as having great capacity, if in spite of a comparatively small power of attraction—that is, longing—perhaps between husbands and wives—nevertheless a great concourse of people was able to find place upon them.) The most convenient condensers are flat, smooth plates of metal nearly in contact.

Very often whole sets of plates are employed, meshing into each other like a couple of combs—as in the moving condensers of a radio receiver. If the plates of the condensers are connected

by a wire (or the islands of our simile by a bridge) the sundered couples rush into one another's arms. Since electrons are able to move freely through a metal, there is now nothing to prevent the reunion. They hurry off through the metal, following the pull of the lines of force—they stream away, and the positive and negative charges are again united. The two electricities have equalized each other through the conductor. The condenser is discharged. The field has disappeared—it collapses into the conductor. A settlement is reached, and peace prevails.

"It should not surprise us, knowing what we know, that the condition of the interval between the plates should play an important part, for it is in this interval that the field is situated. If the field is strengthened in any way—if, for example, we put glass or mica or vulcanite between the plates instead of air—the capacity of the condenser is increased; with the same tension it can now immobilize a greater quantity of electricity. As a matter of fact, it was while experimenting in this direction that Faraday first hit on the theory of transmitted action—the theory of the field.

"It is as though the hope and longing of our islanders were intensified on perceiving that the channel dividing the islands was becoming a swamp. The islands are still practically separate; but the hope has been aroused that it will soon be possible to cross from one to the other, and this hope becomes more intense as the thin surface-crust of the swamp grows firmer. And when it will at last bear the weight of a human being, there is a possibility of direct reunion. It is as though the interval between two condenser-plates were filled with metal, giving direct access across the gap.

"Now there are devices by which fresh electrons can be delivered continuously, so that a constant tension is maintained. To return to our simile of the islands—in the first case there were only a *definite* number of people to march across the bridge. But now more people are constantly appearing on the one island, as though rising out of the earth, and an endless procession crosses the bridge.—And through the wire there is a steady and continuous current of electricity. For the electric current is simply a stream of electrons. On the one side—the negative—the electrons arrive as though flowing from an

inexhaustible source; they stream through the wire to the other electrode, and are thus neutralized. And this goes on until the source is exhausted; the delivery slows down and finally ceases. Then the current dies."

The Electric Current

'The great discoveries are often revealed by the most trivial happenings. You may say that we have electric trams and electric railways today because in 1789 Luigi Galvani, an Italian physician, noticed that a frog's leg was twitching, and did not simply shrug his shoulders and forget about it. Whenever a spark leapt between the electrodes of an electrical machine near at hand the freshly dissected leg, which was lying on a metal plate, suddenly twitched. But it also twitched if it was hung on an iron grille by a copper hook—twitched every time it touched the grille, without the help of any electrical machine. And this was the fundamental experiment, as Alessandro Volta was the first to

recognize, though he did not interpret it correctly. Galvani believed in the existence of animal electricity: Volta advanced a theory of *contact electricity*, which arose at the point of contact of two different metals, and which, on flowing through the freshly dissected frog's leg, caused the muscles to contract. Today we know that two metals and the moisture of the frog's leg were necessary, and that the electricity was generated by a chemical process.

"We will now close the chapter on 'Frictional Electricity.' It was the first form of electricity known; it was not without scientific interest, and it led to further discoveries. But what did our ancestors ever succeed in doing with electricity? They could make little scraps of paper dance, and ring bells by electricity, and draw sparks from their noses. Electricity was a toy for children, or a subject for discussion in the drawing-rooms of enlightened circles.

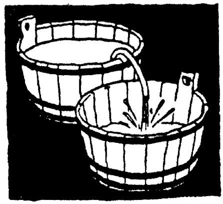
"With Volta's discovery a new chapter in the history of electricity was opened. Electricity was now grown up—it

would soon begin to do real work. The silent, constantly flowing currents of the galvanic elements are unexacting but industrious, full of restrained force. At the beginning of the nineteenth century, the century of *bourgeois* civilization, electricity was still modest and inconspicuous. The voltaic pile stands at the beginning of a development which reaches its summit in the high-tension alternating currents of our own day.

"Today we are all familiar with accumulators and dry batteries, which generate currents of electricity by chemical action. Nernst has given us a vivid picture of the action of a battery-element. If we plunge a metal rod into a liquid, electrically charged ions of the metal are driven out of the rod by 'solution-pressure'; they 'evaporate' as it were, and swim about in the liquid. But this addition is by no means welcome to the fluid; on the contrary, the ions dissolved in it exert a certain force—osmotic pressure, it is called—which tends to dilute the solution—that is, to drive the ions back into the metal. The opposition of these two forces generates an electric tension in the metal rod; it becomes electrically charged, the charge being proportional to the difference between the 'pressure of solution' and the osmotic pressure. If two different metals are placed in the liquid, and connected by a wire, the tensions will be equalized through the wire; that is, a current will flow.

"An accumulator works in the same way—with the difference that it can be awakened to new life, like the phoenix, when it is exhausted. A current is sent through the accumulator, in the opposite direction to the generated current, when it reverses the chemical changes. The accumulator is charged, and is ready to provide a safe, docile, domesticated current. Tension is constantly maintained at the terminals; how, need not concern us just now. There is tension in the conductor, and therefore a field, and the electrons, following the pull of the field, stream through the wire. It is the electrons that carry the current; the positive charges are almost immovable. The wire, of course, is not a hollow tube; it consists of metallic atoms or ions, which are arranged, with a certain degree of regularity, in a structure like a trellis-work of crystals. In this trellis the

electrons are continually shooting hither and thither, with an irregular but rapid movement—about sixty miles a second —even when no tension is applied. If now we press a switch and apply the tension, they all show a disposition to flee from the negative terminal, rushing to the positive terminal along the lines of the field. But they meet with obstacles on their journey; they are diverted and even captured by the ions, when fresh electrons take their place. And so this stream of electrons pushes its way through the wire—like the molecules of a gas that is being sucked through a narrow, half-choked pipe. As a matter of fact, our most recent theories of a metallic conduction are based on this very notion of an 'electronic gas.' Summerfeld was the first to attack the problem successfully with the aid of the theory of gases. This notion is quite actual. Electrons can be shaken like seeds in a pod; by a quick, sudden movement of the whole conductor one can pack them together at one end—as has been proved by experiment.



"The current may be likened to a stream of water, flowing through a pipe, between two tubs or cisterns at different levels. The notion of the strength of current is clear; it is the amount of electricity—or water, as the case may be—passing through the pipe or wire in one second. The tension which generates the current in the first place is equivalent to the difference of level between the two tubs or cisterns. A full cistern is like a condenser; when sufficient water has escaped, and the levels are equalized, the current ceases. But a galvanic element has the faculty of maintaining a constant tension; it is like a pump, which maintains the difference of level between two cisterns; so that the current continues to flow.

The strength of the current of water, it is obvious, depends on the pressure, and it is smaller in proportion as the resistance to its flow is greater—that is, the longer and narrower the pipe, the weaker the current. From this we may deduce Ohm's Law: Current $= \frac{\text{Tension}}{\text{Resistance}}$; and the electrical resistance is

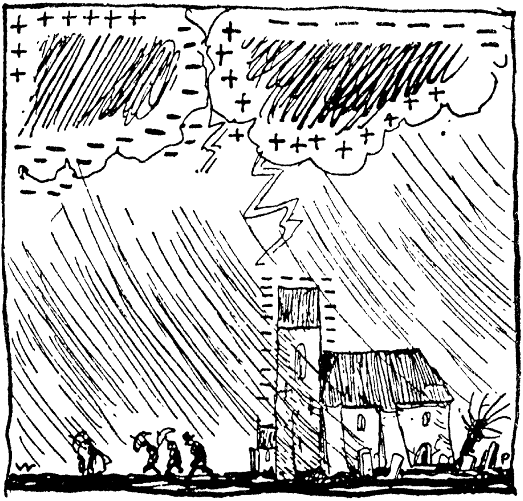
greater in proportion to the length and fineness of the wire. Just as a gas, in flowing through a choked pipe, rubs against the pipe and generates heat, so the 'electronic gas' rubs against the metallic trellis and generates heat by friction—the wire is heated by the passage of the current. Joule discovered the law of this generation of heat by resistance. The heat is evidently proportional to the amount of 'electronic gas,' the pressure which forces it along, and the time during which the current is flowing. Thus: Heat = Current $\times$ tension $\times$ time.

"We have learned the value of this heat; for it makes the filaments of our electric bulbs glow, boils our kettles, roasts our joints, and heats our flat-irons. The amount of heat which a current of 1 ampere and 1 volt will develop in one second is called a *watt*; it is approximately equivalent to the work which the battery or the power-station has to perform in order to generate this current. 736 watts are equal to one horse-power; so that a bright incandescent lamp which consumes 75 watts is constantly consuming about one-tenth of a horse-power; while to the flat-iron, which may consume 500 watts or more, almost a whole horse must be harnessed. Thus the equivalents of work which we are constantly sending through our conductors are enormously large—and inexpensive. If a current furnishes 1,000 watts for an hour, it has done work equivalent to 1 kilowatt-hour; rather more than a horse would do—a 'theoretical' horse, that is; in practice a horse does not perform quite so much work. The current earns anything from a penny to tenpence—the price of a kilowatt in different localities. And with that we have come to the end of the second chapter of electrical doctrine."

"And what about the thunderstorm?"

"Oh, yes, the thunderstorm. I had almost forgotten it. For a long time the physicists could not agree as to where the electricity in a storm came from. Lenard suggested an explanation: The fat, heavy raindrops which fall from the high-piled thunder-clouds are blown about and pulverized by violent, variable squalls. As a result, the charges on the drops are divided. The negative charges remain on the finest particles, and are blown high into the air by ascending currents. The heavy, positively charged raindrops are left behind. In this

way the charges are separated, and so an electric field, a 'longing,' is generated, in which enormous tensions may be attained—tensions of millions of volts—because the charges are widely separated. The stored-up electricity is now waiting to be discharged—and if someone could now lay a wire between the positive and negative regions of the cloud, or from the cloud to the earth, a normal current would flow.



"As a rule, however, there is no one who can lay such a wire—and the electricity seeks its own path. The charges rush forward, following the overpowering pull of the lines of force, ionize the air (which makes it a conductor), and shatter the bonds of the molecules; jerkily, and with rapidly increasing force, they open up their ramified track, making the air incandescent. This is the lightning-flash; sometimes miles in length, but the channel of discharge is quite narrow, and the greater part of the electricity flows along a path only a few centimetres in diameter. There may be a current of 1,000 amperes—but only for a thousandth of a second, and all is over.

"And you see—1,000 amperes flowing for a thousandth of

a second, or one ampere flowing for a whole second is quantitatively one and the same thing.

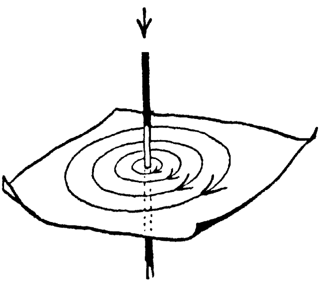
"Actually the quantity of electricity, the 'output,' during a thunderstorm, is very small. The tensions, of course, and the strength of current, are enormous, and so an immense amount of energy is generated; only—and here I must accept the reproach which you made at the beginning of this conversation —we cannot utilize it. For scientific purposes a lightning-flash was once experimentally captured; but it proved to be too capricious. Today we make our own storms. Thunder? Well, you know what thunder is—the air flung aside by the current rushes together again, and sets all the atmosphere about it oscillating in angry sound-waves. But there is a lesson to be derived from this explanation: The clouds, and the rain which they contain, are essential to a thunderstorm; hence, no flash from a clear sky!"

"Oh. So that's a thunderstorm—long drawn-out lines of force. Anything else?"

"No—that ends this chapter. But I should like to go on talking a little longer; who knows when I shall get another chance of talking so much about physics!"

Electricity and Magnetism

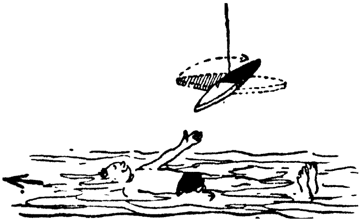
"It was decreed that Hans Christian Oerstedt should be the man to discover the magnetic effect of the electric current. That was in 1820. He had suspended a rotating magnetic needle in the neighbourhood of a platinum wire which he was heating to a red heat by passing strong currents of electricity through it. When he switched on the current he noticed that the needle quivered; impelled



by an invisible force, it swung to one side. When the current was cut off it returned to its original position. At first he

thought the heat was the essential factor; but the experiment succeeded even with weak currents.

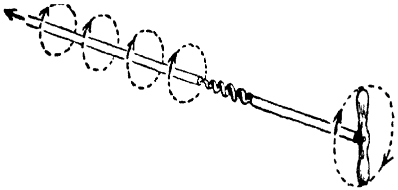
"We, of course, know why. A magnetic needle turns aside —well, we know that there must be a magnetic field there. The current builds up a magnetic field around itself. If we investigate the shape of the lines of force, we find that they are simply concentric circles, the conductor passing through their centre. This field, however—



and this is the important thing to remember—exists only for so long as the current is flowing. It collapses and disappears without leaving a trace as soon as the current is cut off.

"There are various rules by which you can tell the direction of the lines of force. The first is Ampère's rule of the swimmer. If a little man were to swim northwards with the electric current, keeping his face turned to the magnetic needle, the north pole of the needle would turn in the direction of his outstretched left arm; this, then, is the direction of the lines of force.

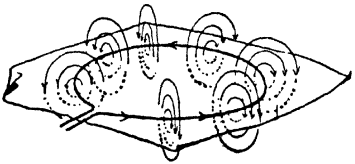
"The second rule comes to much the same thing: the 'right-hand rule.' If the current enters the right hand at the wrist and leaves by the finger-tips, and one approaches the palm to the needle, the latter will turn in the direction of the extended thumb.



"But the best of these rules is Maxwell's 'corkscrew rule.' If you twist a corkscrew pointing in the direction of the current, the direction of the twist is the direction of the magnetic lines of force.

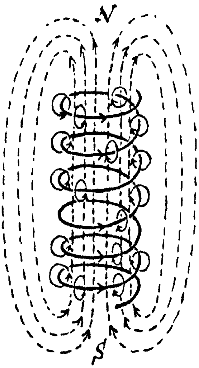
"It is a simple matter to bend the straight conductor into

a loop, so that the current flows in a circle. Then the magnetic lines of force rise up out of the plane of the current, curve round the conductor, and come up again on the other side. Here again Maxwell's rule holds good: twist the corkscrew in the direction of the magnetic lines of force, and its forward or backward motion will give you the direction of the current. I would specially commend the corkscrew rule to you. It is not only easy to apply and to remember; it has also a profound relation—though this, indeed, is cleverly concealed—to the mathematical laws underlying the electromagnetic process. If we wish to determine the field of a cylindrical coil, a solenoid, as it is called, we must add the effects of a number of circular currents. The field of a solenoid looks just like that of a bar-magnet; while a single loop produces a field like that of a thin magnetized steel plate.



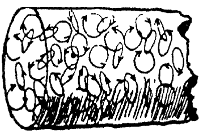
Circular Current

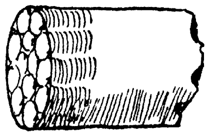
"Oerstedt immediately realized the importance of his discovery. At one stroke he had opened a cross-connection, a bridge, between two departments of physics. Previous to his observation electricity and magnetism had gone their parallel ways as strangers. Of course, a number of their phenomena were closely similar, but there are many such analogies in science. Now, however, it appeared that a current could influence a magnet—that electricity and magnetism were related, were phenomena of the same nature.



"What was the reason? What was the fundamental truth? Was electricity a kind of magnetism? Or was magnetism only a manifestation of electricity? The question was soon answered —Ampère showed that the second hypothesis was correct.

A single loop of current acts like a plate-magnet; Ampère said *as* for *like*. He enunciated the theorem: There are no magnets —there are only circular currents. In any permanent magnet, whether bar-magnet or otherwise, little circular currents of molecular dimensions are permanently flowing. But it is only in magnets that they flow in the same plane, and so reinforce one another. In other, non-magnetic bodies there is no such uniformity, and the currents produce no external effect. Now you will understand what happens when you magnetize a bar of iron; the undisciplined molecular currents are called to order; their planes lie parallel, and so they are able to produce an external effect. In soft iron this order can only be artificially enforced; directly the external field disappears the discipline breaks down and the old aimless disorder recurs. Soft iron cannot be permanently magnetized. Steel is more orderly by nature; once order has been enforced, the molecular currents see no reason to alter their regular arrangement. They remain as they are, and so the steel bar continues to be magnetic.





"In our days, with our improved experimental technique, we have succeeded in obtaining direct proof of Ampère's circular currents. The circling electrons do not weigh very much, but they do weigh just a little, and so each circular current is like a little spinning-top or gyrostat. If we rotate an iron bar at a very great speed the molecular spinning-tops show a tendency to revolve all in the same direction, with their axes parallel to the axis of revolution. The result of this orderly arrangement—enforced by purely mechanical means—is magnetization! S. J. Barnett, in America, was the first to demonstrate this process of 'cold magnetization' (1915). In the same year Einstein and De Haas noted the converse effect: when an iron bar is suddenly magnetized the molecular spinning-tops, as they swing into position, show a tendency to give the whole bar a little twist—a twist which can actually be observed!

"Yet another enigma is explained by Ampère's conception

—and this is a decisive explanation. Why do we never find North-pole and South-pole magnetism separately? We shall understand in a moment.

"Let me ask you a little riddle in physics. On the table before you lie two bars, externally just alike. One is magnetic; the other consists of soft iron. How can you tell which is the magnet?"

"Quite simply—the magnet attracts the other bar!"

"No, no, the attraction is mutual. If I pick up the iron bar and touch the end of the magnet with it I can lift the magnet into the air; it bites as fast as a puppy, when he bites a stick so hard in play that you can lift him off the ground by it."

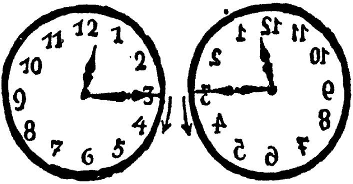
"Aha, I know. You must apply the end of our bar to the middle of the other. Then the magnet will lift the iron—but the iron will not lift the magnet, for every bar-magnet is magnetically dead in the middle!"

"Right. And now for a singular thing.

"The primitive organisms—amoebae and the like—propagate themselves by cell-division. They became constricted in the middle, until they have a waist like a wasp's; they break in two, and the two halves wander away in different directions, two complete and independent organisms. If you cut through the middle of the bar-magnet you will have two small magnets, both complete, with North and South pole, as is only proper. You can make this division as often as you like. This is rather a pity; for an isolated North pole would be useful in Arctic exploration. You would merely have to tie it to a balloon, and following the pull of the Earth's magnetism it would slowly but surely proceed upon its way, and at last, in Northern Canada, though it might be driven hither and thither by the winds, it would gently but decidedly come to rest upon the South pole of the Earth. An ideal postal-service to the land of the Eskimos, who, for their part, would use an isolated South pole to take the balloon back. But there are no such things; as Ampère showed, everything has two sides; every magnetized plate, and every circular current. Sometimes a clock is made with a transparent dial. Seen from in front it is normal; the hand moves to the right at the top of the dial, to the left at the bottom. But seen from behind the hand goes round the 'wrong'

way. If instead of the hand a current were circling round, we should have such a magnetized plate, and we should mark the 'normal' side with an S, and the other with an N. The direction of the circuit depends on the point of view—and every circular current has thus its two kinds of magnetism. So we shall never see such a thing as an isolated North pole, and the Eskimos will have to do without an automatic postal service.

"Ampère really dealt the death-blow to magnetism. Nevertheless, it did not die. People were so used to employing the term that they retained it. It is a fact that a conductor carrying a current—for example, a solenoid—builds up a field about it which exactly resembles the field of a bar-magnet—that is, a magnetic field. If we cut off the current we then have a charged wire, in which electricity *is* but does not *flow*; so the field collapses and disappears. The normal electrostatic field is left—but that has quite a different appearance. Its lines run perpendicular to the magnetic lines, and they have no effect upon a magnet.

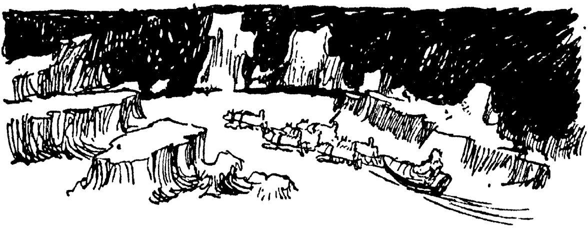


"It would never have occurred to Oerstedt's magnetic needle to rotate on entering an electrostatic field. There are two fundamentally different kinds of fields: electrostatic, called electric for short, such as form about any electric charge, and fields of the second kind—*magnetic* fields—for so we shall still so describe them—which depend on the presence of *moving* charges."

The Induced Current

"And now for the second cross-connection. A current gives rise to magnetism: that we know. Can a magnetic field give rise to a current? A man of Faraday's calibre spent years and decades in the search for the answer to this question. Only his adamantine conviction that this *must* be possible gave him the strength to persevere. For years, it is said, he carried

a little magnet and a bit of copper wire about with him, so that he might constantly be reminded of the problem. This is a pretty example of the fact that physical experiments are not made at random; that the experimenter works in accordance with a plan, either based on a theory or suggested by some still nebulous and intuitive conviction. The experiment by which Faraday at last reached his goal is almost absurdly



simple. A loop of wire is brought into a magnetic field and connected with a galvanometer. At first, we'll suppose, it lies parallel with the lines of the field; then it is suddenly rotated through an angle of 90°, so that the lines of force cut across the plane of the loop. When this is done the galvanometer-needle suddenly swerves aside, and then returns to zero. By merely revolving the loop a short rush of current has been generated in the wire. In general terms: in an electric conductor which is so moved in a magnetic field that it cuts across the lines of force a current is 'induced.' The magnetic field is enabled to generate electricity. And again the analogy is perfect—just as only a *moving* charge can set up a magnetic field, so this induced current appears only in a *moving* conductor."

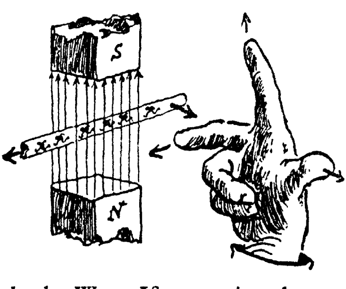
"A pretty experiment! Scientifically interesting, simple, and harmless—was it anything more?"

"It seems simple and insignificant enough. But whether we travel by electric railway, or turn on the electric light, or instal electro-motors in our factories with an output of thousands of horse-power, or switch on the self-starter of a petrol driven car, we are always making use of Faraday's induced currents. Today they rule the world."

"That sounds rather queer, doesn't it? That a current sets up a magnetic field around it I can understand; you have told us—haven't you?—that electricity and magnetism are related. Though for my part I feel they are both equally mysterious; non-existent, so to speak; two phantoms that speak a mysterious, esoteric dialogue. Well, let them—I'm content to leave them to it. But that in a palpable bit of copper wire, simply because I pick it up and move it over a magnet—both sane, material things with two feet on the ground, so to speak—such a mysterious thing as electricity should suddenly appear—well, this mixture of the tangible and the immaterial goes against the grain with me! It's like meeting a ghost in broad daylight."

"Well, there's only one answer to that. I won't inquire which is really the more 'material'—the despised electricity or the 'tangible' copper wire. We must simply learn the grammar of the phantom's language, and its laws; for since Hittorf's experiments we can swear to the existence of pure electricity—the electrons, you'll remember. Well, if an electron is shot into a magnetic field it is turned aside.

"Amidst the ice of the Antarctic is the place where the magnetic lines of force rise vertically from the 'Earth,' which the geographers, by reason of its southerly position, wrongly call the South magnetic pole. Sir James Ross was the first to search for it. If Sir James could have sat upon an electron instead of a dog-sledge, he would have made an incomparably quicker journey, but he would never have found the magnetic pole. The electron, coming from the North, would inevitably have turned off towards the West. If a negative electron moves in a magnetic field at right angles to the lines of force, it will be pushed aside by a force action at right angles to the direction of its motion, and also at right angles to the magnetic lines of force. The three directions: electron-path, magnetic



field, and diverting force, are all at right angles to one another like the three corner lines of a cube, or the thumb, forefinger, and middle finger of the right hand.

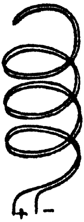
"And now, you must think of the electrons as enclosed in a tube—as an 'electronic gas' in a piece of copper wire. If I keep the wire horizontal and push it across a vertical magnetic field, the diverting force acts upon the whole of the electrons. They begin to wander through the wire in a leftward direction, and a current flows through the wire—an induced current! But if I hold the wire in a vertical position, parallel to the lines of force, the electrons try to move across the wire; they are piled up on one side of it, and no current will flow along it. Like you, they have forgotten that there is a 'ghost' even in the interior of a tangible length of copper wire.

"We must consider this induced current a little more closely. It has been shown that a current arises in a conductor—in other words, is induced—when it is moved in a magnetic field in such a way as to cut across the magnetic lines of force. But we can equally well have a motionless conductor, and move a magnet—a bar magnet, for example—past the conductor, carrying its field with it. Here again the conductor cuts across the lines of force, and a current is induced. Or we can generate the magnetic field electrically—that is, we can run two wires side by side and pass a current through one of them. When the current passes this conductor builds up a magnetic field, and if we move the second conductor through this field a current will be induced in it. Or we can cause *temporal* instead of *spatial* changes in the field. For example, we can slowly build it up by slowly increasing the current in wire No. 1. More and more numerous lines of force come into being which were not there a moment ago—so that in this case also the second wire is cut by lines of force, and a current arises in the conductor. Again, when the current in wire No. 1 is suddenly switched on a current is induced in wire No. 2. The more rapidly the current is switched on, the shorter is the interval of time into which the alteration of the lines of force is compressed, and the greater is the tension induced. *The induced tension depends upon the rapidity of the alteration.*

"Here, you see, is yet another step forwards. Static charge—

electrostatic field. Moving charge (current)—electromagnetic field. Moving current or changing current—variation of the field, and induction of tension. Each alteration brings something new into being.

"These laws are rigidly correct. We conclude from them that a current must even be able to act upon itself, for when it has built up a magnetic field around it, then it is merely a conductor in a magnetic field. It doesn't matter where the magnetic field comes from. When it is altered—as, for example, when a current is switched on—it excites an induced current in the conductor—taking no account of the fact that it owes its existence, in the first place, to this very conductor. In other words, the children turn against their parents. The induced current is always so directed that it seeks to retard the alteration in the magnetic field—it seeks to undermine the cause of its own existence; its temperament is suicidal. Thus, when we switch on a current of electricity the induced current—or *extra* current, as it is also called—acts against the main current, causing a slower rise of the current to its maximum; that is, a *retardation*. In closely wound



reels or solenoids—the coils of electromagnets, for example—this effect may be so considerable that some seconds and even minutes pass before the current reaches its full strength. If we switch off the main current the induced or extra current seeks to maintain the magnetic field—it flows in the direction of the main current, reinforcing it. The induced tension of interruption is superimposed on the working tension, and may lead to tremendous bursts of tension which may endanger the circuit. But everyone who has ever worked an uncovered switch will have noticed the spark, which derives its potential from the induced extra tension.

"The reaction of a conductor upon itself depends very largely on its geometrical form. In long, narrow solenoid coils, for example, the total effect of the variation of the current is felt by the conductor; in other words, they have a high *self-induction*. On the other hand, a wire coiled as you see it here shows no reaction whatever, as the magnetic fields of the currents going and coming compensate each other; their effect

is nil, and remains so even when the current is 'made' and 'broken.' Resistances which are required to be non-inducting are therefore wound in this 'bifilar' form.

"Here, then, are the fundamental points of electrical doctrine: A charge generates an electrostatic field. Electric current, a flux of charge, is made possible because by chemical processes a difference of tension can be permanently maintained, so that fresh charges are continuously delivered. An electric current is surrounded, as long as it flows, by a magnetic field. Every magnetic field generates a current in a moving conductor. In the two latter cases the movement of the conductor and the variations of the current are significant.—And on these simple facts, which, of course, to this very day are still unexplained miracles, and may quite possibly remain so, the whole science of modern electrotechnics is built."

And so ended this conversation, which had been started by a defective cable and a thunderstorm.

Energy transmitted through the Air

We wandered over the moor. In a long, rhythmical line, which caught the eye even in the distance, the gentle curves of the high-tension conductors ran across country. The trellis-work of the pylons was slender, yet strong and rigid. The indented chains of porcelain insulators had the look of fantastic toys. And presently the six strong copper cables were overhead, and the wind was humming gently through them.

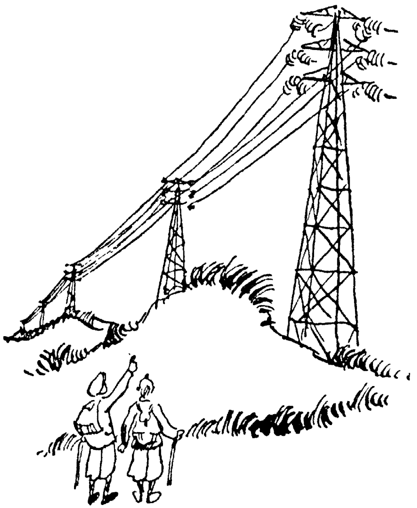
"It's queer," said my friend, "to think that in these copper cables, no thicker than two fingers, over 27,000 horse-power are rushing toward the city. 220,000 volts tension; a current of 100 amperes. And when you look at the cables you see nothing, absolutely nothing of this terrific flood of energy."

"That's so," I said. "But this is even queerer: the cables are hollow. The stream of electrons flows only on the outside of the cable, so that a hollow tube will carry it just as well as a solid rod. And this is queerer still: this tremendous stream of electrons is not the real current. The cable doesn't contain

the energy at all. The current is there, of course; it is even a necessary evil. But the energy of the dynamos which are capable of lighting a whole city—this energy doesn't flow through the cables."

"How so?" asked my companion. "It can't travel to the city through the air?"

"But it does: *the energy travels through the air*. The current



builds up its field around it, the electromagnetic field. This field, and this field alone, contains all the energy. A current of energy rushes along the cable with the speed of light. Along the cable, but not in it. The field, in the open air, contains all the energy of the power-station. Indeed, you may see, when the current is suddenly cut off, how the energy of the collapsing field, suddenly breaking loose, seeks a path through sparks a yard long as the switch is thrown open. The current is a necessary evil—necessary hitherto, but not really desired. It is needed in order to hold the energy together, in order to guide it along the cable. Otherwise it would be scattered to the four winds. Even indoors, when I switch on the lights,

this invisible, mysterious flood of energy runs through the air along the lead, and across the wall to the lamp. Once you accept the field theory of Maxwell and Faraday you must be consistent. *The energy is in the field.* One day, perhaps, it will be possible to dispense with the wire altogether." And I pointed across the broad, shimmering surface of the estuary. Just visible in the early twilight the slender, fragile towers of the radio transmitting station rose into the sky. "Over there the aerial radiates 150 kilowatts; scattering its energy unselectively in all directions. That is why you capture only a fraction of a millionth part of it in your radio receiver, and why you must artificially reinforce this insignificant remnant. But recently they've been making directional aerials, which emit all their energy in a definite direction. Directional transmitters—'beam wireless' stations—are sending messages to the Far East, to America and South Africa. Light a great lamp on one of the towers there, and even with a million candle-power you won't be able to see by its rays at any distance. But collect its energy in a searchlight, which concentrates its rays into a narrow bundle, and you can see a house or an aeroplane miles away as plainly as though it were day. And of course, where the finger of the searchlight is not pointing—even a couple of yards away—everything is dark. When once it is possible to build searchlights for the long electromagnetic waves—and as I've said, we are well on the way to doing so—we shall be able to send energy freely through space. The 'beam wireless' to South Africa can't be heard in France or Poland—but it is heard admirably in Capetown. In twenty years' time, or a hundred, energy will be radiated to the cities without such costly and complicated crutches as our present cables. We shall transmit energy to inaccessible mountain observatories, aeroplanes in flight, and little islands overseas in a narrow, concentrated bundle, directly through space. The age of electricity is only beginning. We are still shooting sparrows with cannon; anarchy prevails in the ether. But a time will come when electricity will again be free from the fetters of matter."

It was growing dark. We were still standing below the high-tension conductors, and we cast a last glance at the

strangely inspiring curves of their slender cables. Twenty-thousand kilowatts were rushing alongside these cables to the city. For a moment it seemed as though I could see this immaterial energy, surrounding the wires in a radiant sheath. . . . But we moved on. A physicist must not let an irrational vision have its way with him.

A field of corn spreads its lustrous flood over the bright landscape. It shimmers gold in the glowing sunlight, and a few butterflies, in their aimless, incalculable flight, are dancing through the quivering air. The summer wind is rising; a hot

wind, blowing strongly across the rustling cornfield. With a soft, rhythmic movement the heavy ears bow on their slender stalks, till they point quiveringly downwards; bowing no longer when the wind has passed, they lift themselves, still swaying a little, and are still once more. Broad waves pass over the cornfield, running before the wind; a wide, harmonious, rhythmic movement, a wild, convulsive lashing and fluttering under the sudden, unexpected gusts. We can see the waves racing over the wide field until they disappear from sight over the crest of the low hill.

A wave runs over the field. Sometimes, perhaps, on such a summer day, as you lie in the shadow of a bush, it may happen that your eyes are captivated by the mysterious harmony of this movement; they wander across the field with the wave, and then leap back to the next one—spellbound by the hidden loveliness of this movement, by the compelling charm of the rhythm. Or was it something more than this? Were your delight and your reverent wonder more conscious? Were you

suddenly made aware of the enigma of the wave—that process at one and the same time so strangely material and immaterial? Perhaps it was beside such a waving cornfield that you first became conscious of the twofold nature of the wave.—The squall is over; a gentle quivering, and the slender stalks are standing erect as tapers, apparently unmoved; yet only a moment ago a wave passed over the field, and every one of these stalks bowed deeply, striking against its neighbours, and communicating its unrest to them.

After all, each stalk remained in its place; it didn't grow legs and run across the field. What did run across the field was simply the movement, the condition of restless oscillation —the wave. It is just the same with the great, silent swell of

the ocean, which represents the purest form of the waves of the sea. Here too it is only the wave that rolls on across the sea; the individual particle of water dances up and down, but keeps its place.

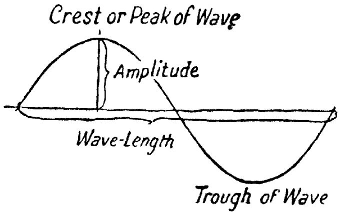
As children we have often amused ourselves by making waves run along a cord: a clothes-line, a rope lying on the ground, or held between two children. With a short, sharp movement one jerks the rope up and down again—one gives the impulse, and the process continues of itself. By reason of the internal cohesion of the rope, each particle, as it flies upwards, carries the next with it, reaches its highest point, and moves downwards again. It has passed on the impulse, and if this impulse is repeated at short, regular intervals what we call a "standing wave" is formed. The whole cord assumes the wave-formation, every little part of it constantly dancing up and down.

The expression "standing wave" must not be misunderstood. The waves still run the whole length of the cord, and back again. The essential thing is that the wave-lengths—the dis-

tance from one wave-crest to the next—become so equalized that the returning waves fit smoothly into the outgoing waves.

Here I am afraid we must learn a few technical terms.

By *amplitude*, or height of wave, we understand the vertical difference between the crest of the wave, or the trough, and the mean position. The *frequency* or number of oscillations (they are sometimes measured in "Hertzes," when the symbol Hz is employed), tells us how often each particle swings up and down in a second—from the crest, down to the trough, and back again to the crest. The time which it requires to do this is the *period of oscillation*. With a frequency of 50 Hz—i.e. 50 oscillations per second—the period of oscillation is one-fiftieth of a second; the two magnitudes being in inverse ratio, or *reciprocal*.



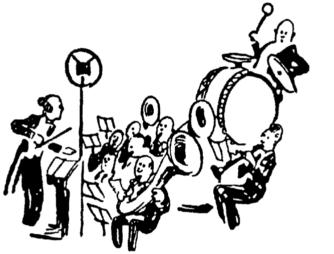
In this fiftieth of a second a whole wave-length has apparently pushed its way through the position of the moving particle, and in this fiftieth of a second the wave has moved one wave-length—let us say, for example, 1 metre—to the right. In a whole second, therefore, the wave-motion has travelled a distance of 50×1 m. $= 50$ m. forwards; and this is its velocity—the rate of propagation of the wave. So

$$\text{Velocity} = \text{Frequency} \times \text{Wave-length.}$$

Radio waves, for instance, have a velocity of 300,000 km./sec.; therefore a wave of 300 m. has a frequency of 1,000,000 Hz $=$ 1,000 kc. (kilocycles, a kilocycle being 1,000 complete oscillations). If you like, you can examine the figures of all the radio stations, to see if this relation holds good. The wave-length gives, so to speak, the length of the stride; the frequency is the number of strides per second of the wave—the thing that runs across a cord when we shake it. The harder we shake the cord, the higher will be the crests of the waves. It is the amplitude alone that determines the energy of the wave.—But that's enough for today.

Electromagnetic Waves

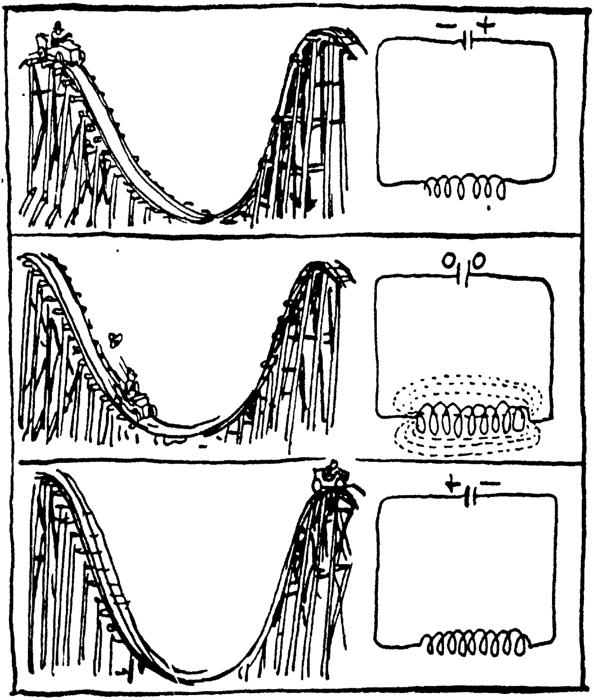
"The Chinese will hear it sooner. . . ." A tin placard with a big I on it was hung up outside the bandstand, and the conductor of the municipal orchestra of Shingleton-on-Sea lifted his baton. But then he gave a signal which meant "Hold on!" or "Stand by!" A man in a white overall ran forward, fixed one of the microphones in another place, and then withdrew, carefully paying out the smooth, black cable behind him. There must be no technical hitch in the broadcast of the municipal orchestra!—Then, with a prolonged roll of the drums and the din of many brass wind-instruments, the music struck up, and the merciful sea breezes carried the sound away with it.



"The Chinese will hear it sooner!" repeated the tall, thin visitor, after the orchestra, as though itself rather startled by the effect of its opening effort, had entered upon an easily-flowing descriptive passage. "It really is the case: every Chinese or Australian who is listening to the broadcast beside his loud-speaker will hear this music just a little sooner than we do, sitting in our chairs on the parade, barely a hundred yards from the bandstand. Not much sooner—but all the same, before we do!" His plump little neighbour polished his pince-nez and incredulously shook his head. Yet the tall, thin man was right.

We will confirm his statement. But we shall have to approach the subject in a roundabout way. Do those men over there in shirt-sleeves, high above the ground, who are building in the meadow the scaffolding of a switchback railway, realize that they form an important link in our demonstration?

We will consider such a switchback railway. We release the car at the top of the track. It begins to roll downwards—for thanks to its elevated position it has acquired energy (since someone had to perform a great deal of work in getting it up there in the first place), and this energy can be transformed



into motion. So it rolls on, faster and faster, till it comes to the bottom of the dip. There it has no height or potential energy left, but it is now in rapid motion. Its energy is concealed in its velocity; it has not disappeared, but has only disguised itself. And we see now how the car shoots past the middle of the dip, and how its movement enables it to climb the opposite slope, until it finally comes to rest at the top of the last ascent.

Electricity can be made to oscillate in the same way. We connect up a condenser and a self-induction coil, charge the condenser (from a battery, which is then switched off again), and we have a certain amount of energy stored up, just as it was stored up in the car at the top of the switchback railway. Now we close the switch; the condenser discharges itself, and a current flows through the coil. And with this the effect is produced of which we have already spoken—the coil builds up its magnetic field. The tension in the condenser has equalized itself; the electrical energy of the field has disappeared. (This is the moment when the car rumbles noisily across the bottom of the dip.) And here, too, the energy has only apparently disappeared. For now, when the current of discharge ceases to flow, the magnetic field has lost its *raison d'être.* It collapses, and as it alters, decreasing in strength, it induces in the coil an "extra current"—and in this induced current the energy reappears. *The current flows again, in the old direction,* fed by the collapsing magnetic field. And it charges the condenser—for the electrons of the current pack themselves into the right-hand plate of the condenser, since they cannot go any farther. When the magnetic field has sunk to zero it can no longer maintain the induced current. The condenser is charged once more, although the field now runs in the opposite direction: the switchback car has reached the top of the opposite incline. The position is now this: a fresh electric field between the plates, a charged condenser, and no magnetic field about the coil. And as the car turns about, so the current begins to flow again (but now in the opposite direction!) and builds up a new magnetic field—and so the process continues. The electrical energy oscillates rhythmically to and fro. We have an "oscillatory circuit."

We have seen that the magnetic field plays the part of the heavy mass; the car, thanks to its inertia, rolls on and up the opposite incline; the current, thanks to the inertia of the magnetic field, continues to flow even when the condenser is discharged. But even here losses are unavoidable; only in an imaginary experiment can they be left out of account. The oscillations are "damped"; like a pendulum, whose bob moves ever more slowly, less energetically, so the oscillations

of the electrical circuit gradually diminish, and at last die away altogether. But it is these very losses that have made broadcasting possible!

Take note of this: When an electrical circuit oscillates it makes a definite number of oscillations per second, which is dependent only upon the size of the condenser and the self-inducting coil; just as the oscillation-period of a pendulum is dependent only upon its length. By varying the capacity of the condenser or the self-induction of the coil we can vary this inherent periodicity within certain limits; in other words, we can "tune" the circuit to different frequencies. Let us note this also: The field possesses a certain inertia; it is very conservative, and resists any change. The field, in short, refuses to be hurried. Where does it get this inertia? For a field, after all, is something quite immaterial, incorporeal—a mere condition, a capacity. How can such a spooky sort of thing possess inertia, like a heavy body?

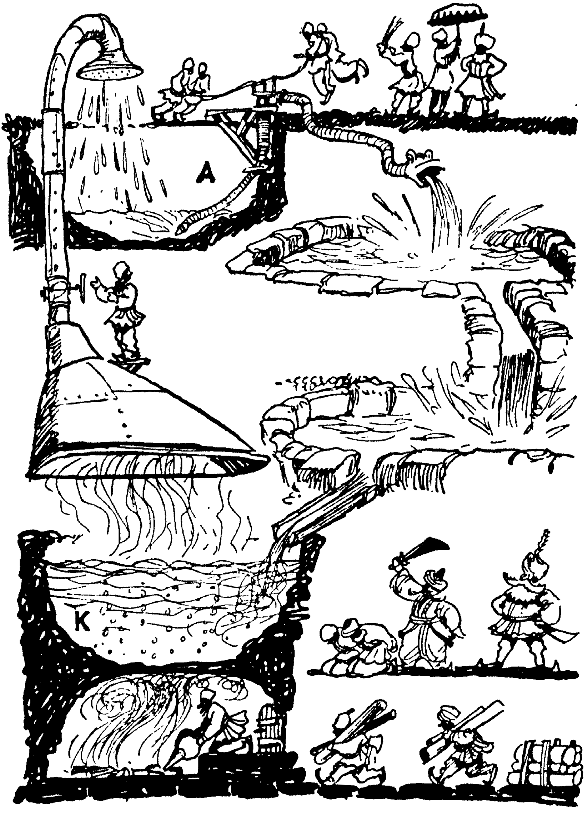
Well—a field represents a certain amount of energy. And energy possesses inertia. When a magnetic field breaks down its energy must go somewhere; it can't simply disappear into the void. It resists being suddenly transported to another point of space. It doesn't see what anyone is going to gain by the change—so the transportation of energy takes a little time. And here is something more to remember:

The notion of the field is like the notion of transmitted action, and is akin to the concept of *a finite propagation-velocity of energy*. No theory of action at a distance can possibly determine the velocity of propagation. This is a question to which such a theory *can* give no answer; for it refuses, on principle, to consider the mechanism of transmission.—But we shall return to this point in a later chapter.

The Electron-Tube or Radio Valve

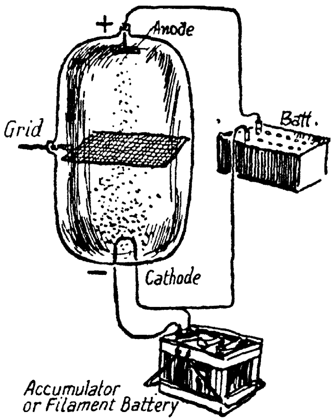
Let us suppose that the Great Shah of Persia had a crazy sort of hydraulic system constructed. A pump continually pumped water out of the pond, A; it ran, through basins and conduits, into the pond K. With what result? In a little while A was empty and K full to overflowing. In such a case we

cannot speak of a hydraulic circuit. The architects and hydraulic engineers were beheaded, but the circuit was not perceptibly improved thereby. Then the Court Fool Nasreddin appeared, and said: "You just let me get to work; the usual



reward, of course." And he proceeded to light a great fire under the pond K. The water boiled and bubbled and evaporated; a dense column of steam rose from it, and was condensed into water, which fell back into A. So, by dint of evaporation, the water was transported across empty space. The electron-

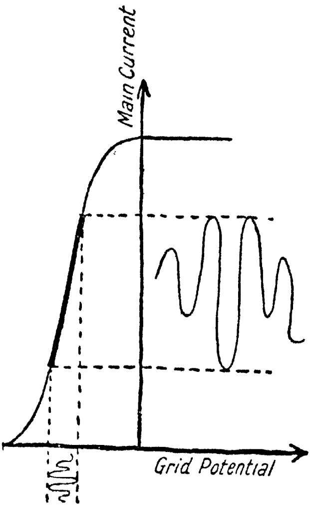
tube or radio-valve acts in a similar fashion. No current can flow through a tube that has been pumped quite empty of air, however great the tension in the electrodes. The electrons are numerous enough in the wire of the cathode, but they cannot escape from it. The only thing they can do is to evaporate. The cathode wire is heated to a bright red heat; and then the electron-gas evaporates from the wire, for now it can pass the relaxed and softened surface. A thick cloud of electron-vapour forms about the cathode, and the density of the electron-cloud, the electron-vapour, can be calculated by the same formula which is employed for the evaporation of a fluid. We say that a "spatial charge" has formed itself. Of course, the repulsion of the negative cloud opposes the efforts of further electrons to evaporate, and so the process would soon come to a standstill if the ever-hungry positive anode did not constantly suck wisps of the cloud towards it. With tremendous velocity the free electrons rush through the glass bulb—a stream of electrons, like the current of steam in Nasreddin's machine. But fresh electrons emerge from the glowing cathode to take the place of those that have flown off. So the various forces come to a "gentleman's agreement"—and a current flows through the vacuum.



"Very good indeed," said the Shah to Nasreddin, "but there is still one defect. We must have some way of regulating the stream! Sometimes I want to send less water through my garden, and sometimes more."—"All right!" answered the fool—and he proceeded to construct a regulating valve in the steampipe; and when he opened this valve more or less widely, more or less steam passed through it, and this proved to be

an excellent means of regulating the flow of the water.—Well, the electron-tube or valve also is given a regulator.

This is the *grid*—a wire grid, set across the path of the electrons. To begin with the grid does not disturb them greatly. But if the grid is negatively charged it repels a certain proportion of the evaporating electrons, reinforcing the repressive action of the cloud. And this negative charge can be made so great that not a single electron flies up to the anode. True, the goal is enticing, and the attractive force of the anode may be great. But nearer and larger is the mysterious, abhorrent obstacle of the negative grid. The electron is left disconsolate in the gap between the cathode and the grid. As you see, the grid acts as a *valve*. By grid-charges of differing strengths the stream of electrons which it allows to pass is automatically weakened or reinforced. The stronger the negative charge on the grid, the more vigorously does it repel the electrons, and the fewer electrons reach the anode; but as soon as there is a small decrease of the negative charge, or the slightest tendency to become positive, a great crowd of electrons overcomes the obstacle and flies to the anode—a powerful current. The process is like the high jump: the higher the bar, the fewer the men who can jump over it; there are many jumpers who can clear 5 ft. 10 in., but the slight increase of 2 inches will defeat the majority, while over 6 ft. 2 in. every fraction of an inch will enormously decrease the number of competitors.



This is the essential feature in any sort of valve: great forces must be controlled by small. The engine-driver turns a throttle-lever with his hand—and the thousand horses of

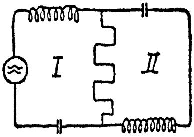
the express locomotive obey the movement. A slight pressure of the foot on the accelerator—and the 100-H.P. omnibus increases its pace. A very slight variation of the grid tension is enough to control the many amperes of a great triode valve. If the grid tension varies in pulsations the powerful current of the main circuit pulsates in time with it. We must remember that the electrons are incredibly light—that they have no mass in the ordinary sense of the word. Consequently they obey each impulse immediately; whereas the omnibus takes a little time before it reaches a higher speed, the main stream in the triode valve obeys the orders of the grid *instantaneously*.

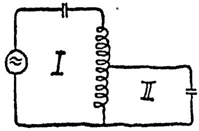
This explains the amplification effected by the triode valve—though this, as we have seen, is not really an amplification: we rather *replace* the weak current of the grid by the very much stronger main current—which faithfully reproduces all the vicissitudes of the grid current.

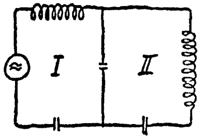
Back-Coupling

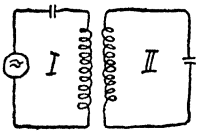
Now we can return to our main problem—how can the losses in our oscillatory circuit be made up? To be sure, the pendulum of a clock swings day in, day out, without slowing down. But it makes use of a mechanical device: every time it swings back it is given a little push. A toothed wheel, driven by a heavy weight, makes a fractional revolution, and gives the pendulum the necessary additional impulse. And this is the essential thing—the pendulum itself releases the escapement-wheel at the right moment—otherwise the clock would not go—and so controls the working of the clock. Meissner succeeded in solving the same problem in the case of oscillatory electrical circuits. An oscillatory circuit is hooked up. It corresponds to the pendulum. It needs constant energy, which is taken from a battery. The battery corresponds to the weight of the clock. And this energy must be applied at the right moment—and for this purpose the clockmaker employs an escapement which is released at the right moment by the pendulum itself. And we use a triode valve, whose grid is operated by the oscillating circuit itself, so that it always lets an impulse of current through at the right moment.

The magnetic field of the oscillating circuit embraces the grid coil also, and by its collapse induces in this coil a current which alters the grid potential. The circuit is "back-coupled" to the grid. And it is evident that the grid will necessarily follow the same tempo as the oscillating circuit—and thus that the anode current will be controlled in the same tempo. So the current in the oscillating circuit swings to and fro automatically, until the inevitable losses bring it to a standstill. Once set going, the circuit oscillates until the battery is exhausted—just as the clock goes until the weight has run down.









Something more must be said about *coupling*.—We have two oscillatory circuits: the first is in some way traversed—for example, by means of a sparking coil—by constant electrical oscillations. How can we impart some of this energy to the second circuit?

Well, we can give the current access to the second circuit by simply joining the two circuits together. The expert will call this a case of galvanic coupling, and will go on to speak of resistance-coupling and capacity coupling (see the first and second sketches). You will see that the oscillating current of Circuit I spreads into Circuit II and excites oscillations there also.

The expert now proposes a third possibility: capacity-coupling (condenser-coupling, as in the third sketch), and finally a more indirect kind of coupling: inductive coupling (as in the fourth sketch). Here there is no conductive connection between the two circuits, but the magnetic field of Coil I surrounds Coil II also, and when the strength of the field varies in time with the oscillations it induces in Coil II, and therefore in the whole of Circuit II, an oscillatory current.

Now, with all this newly acquired knowledge, it is time to

venture a step into the unknown. We will couple—inductively, we will say—a long, straight wire, the antenna or aerial, to an ingenious system of oscillating circuits, the transmitter. And now we can go ahead. The engineer switches on the current to the heat-generators, the filaments grow hot, cold water pours through the coiled porcelain tubes that surround the transmitting-valves, with their 12,000 volts of anode potential—and then he throws in the last switch; an electrical impulse rushes through the circuit, swings to and fro, acts upon the grid through the back-coupling, and begins to oscillate with frantic energy. One after the other the amplifying circuits are thrown into oscillation; the last of them is coupled to the antenna, and so we have a current ceaselessly swinging to and fro in the aerial.

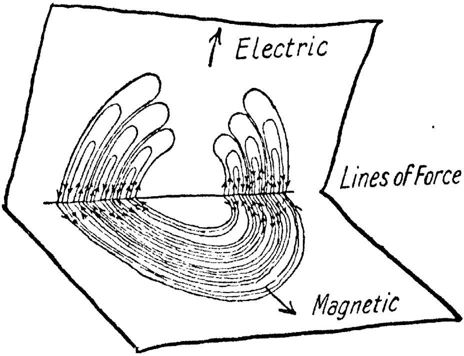
There is a device which is often employed in the cinema in order to demonstrate—for example—the technique of a high jumper. The picture is suddenly brought to a standstill, when the jumper, in frozen beauty, hovers above the bar. We will do the same thing. The current is flowing in the antenna; we will suddenly cry "Halt!" and see what we have there.

Aha! Here is an electric field, whose lines proceed at right angles to the conductor, and a magnetic field also, which lies in circles round the wire. This is nothing new to us. But if we consider this frozen condition a little more closely we see this: The magnetic field around the wire has grown out, in this short interval of time, to a certain distance from the aerial—let us say, a hundred metres. But the boundary between field and not-field, between tension and no-tension, is, as we see, restless and unstable; it will immediately push itself farther out if we give the word "Go!" It is the same with the electric field, and we know the velocity with which the electric and magnetic fields propagate themselves in space—it is 300,000 km./sec. Do you perceive once more the influence of Faraday's theories of contiguous action?

Let us give the order: "Carry on!" The broadcasting process commences. But because the aerial is coupled to an oscillating circuit, the direction of the current in it is now reversed, and the lines of the new magnetic field run round it in the reverse direction. A system of concentric rings, constantly changing

their direction, the magnetic fields fare forth into the world at a speed of 300,000 km./sec.—as alternating fields.

With the electric fields the case is rather different. When the potential in the aerial gradually sinks, and falls back to zero, this is the signal for the lines of the field to turn back, to withdraw themselves into the conductor. Those lying nearest to the conductor manage to complete the homeward journey. But those that have already ventured too far into the unknown soon discover that they cannot possibly get back in time. So



they make a virtue of necessity; they cut themselves loose, form an electrical eddy, and go out into the world as such. Vortices of electrical power, one after another, they tear themselves loose and set out on their long journey. The electrical field also is an alternating field, and travels at the rate of 300,000 km./sec.

The aerial forms an *open* oscillatory circuit; and it is precisely owing to the extended, open formation of the circuit that such a large proportion of the electrical and magnetic lines of force are able to cut themselves loose and fly off. Of course, we must think of the lines of force which are shown in cross-section as rounded out into shells.

The aerial is now radiating. It is sending spherical electromagnetic waves out into space—waves which oscillate in time with the oscillatory circuit of the transmitter. At every point of space the alternating electromagnetic fields go racing by,

and always the electric and magnetic lines of force are at right angles to one another and to the direction of propagation.

Broadcasting

The waves travel through the air, and the air is full of electrical life. Electrons inhabit the air, and ions, which are due mainly to the action of the sunlight, and are neutralized again at night. They are all thrown into oscillation by the passing waves, and so a little of the energy of the waves is lost. The air is a *turbid* medium for the electric waves; and the "livelier" it is, the more turbid. This is why radio reception is better at night than by day, and better in winter, when the sun is only a few hours above the horizon, than in summer.

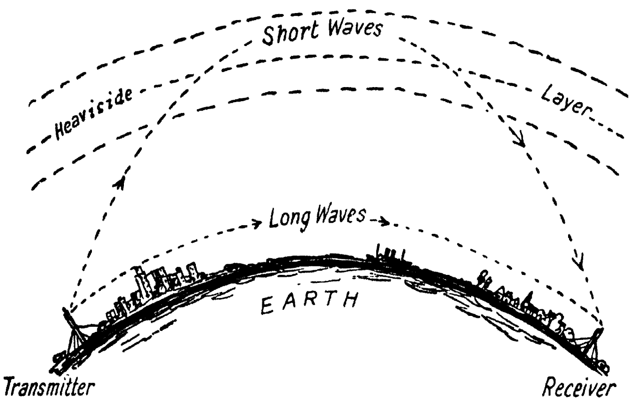
We know from experience that long, slowly oscillating waves penetrate a turbid medium better than short waves. From prehistoric times the aborigines of South America and Africa have telegraphed to one another by means of the deep, rumbling tones of signal drums—that is, by means of long sound-waves.

The longer the waves, the better, generally speaking, will reception be—the more reliable, whether by day or night. For this reason, in the early days of wireless transatlantic telegraphy from Nauen, gigantic waves of 20 kilometres (over twelve miles) were employed. Such a wave runs along the surface of the globe, and the electrical lines of force are at right angles to the Earth's surface. They run along the ground as they would along a wire, since the Earth is a conductor for electricity. We call such waves ground-waves. The shorter the wave, the larger the fraction which escapes from the ground; and this is particularly large in waves of less than 100 metres. They rise steeply into the air; it was formerly supposed that they were lost in space.

Surprisingly enough, certain American amateurs, to whom this useless band of wave-lengths was generously surrendered, succeeded in covering enormous distances, and even in bridging the ocean—and this with a fraction of the power employed by the great transmitting stations. Today we know the reason. At a very great height above the Earth—fifty or sixty miles—is a strongly conducting layer of electrically charged particles

of air—of ions: the *Heaviside layer*. From this the radio waves are thrown back—reflected. It is just as though the Earth were surrounded, at a distance of fifty or sixty miles, by a metallic shell!

The height of the layer has been determined by electrical soundings: a short, sharp signal is sent upwards, reflected from the layer, and returned to the sender. It returns in something like a thousandth of a second, and this interval of time can be very exactly measured.



So the short waves travel, as regards the greater part of their path, through the "ionosphere," unhindered, and return to earth again, after a long journey, still comparatively strong. Hence the often surprisingly good reception of short waves emitted by transmitters of very low power. Unfortunately, the Heaviside layer may refuse to function properly. It grows restless; it may even suffer distortion, or become, for a time, a bad conductor—and then reception grows weak and indistinct. slowly recovering itself only when the Heaviside layer has grown calm again. We call this *fading*. After all, the Heaviside layer is *not* a metallic shell!—Between transmitter and receiver there may be a zone where short-wave transmissions cannot be heard at all—a "silent zone." It is an interesting fact that such zones of silence and such abnormal ranges have been observed

also in respect of the sound of great explosions. Sound-waves too travel far up into the stratosphere, and are reflected back to earth by a warm layer of ozone, about twenty-two miles above the ground.

Every electrical oscillation, every variation of a current, involves a variation of the field, an electro-magnetic disturbance which is propagated through space with the velocity of light. If I switch on an incandescent bulb, lit by an alternating current of 50 cycles to the second, it is transmitting electrical waves about 6,000 kilometres in length. Of course, the energy of the waves is very small—and of course, quite apart from the great length of the waves, the lamp is not built for transmitting. But it often happens that electrical apparatus—especially appliances worked by high-frequency currents, such as vacuum-cleaners, motors with sparking commutators, refrigerators, etc.—emit perceptible waves, which fall within the limits of the broadcasting bands. In a house where such appliances are being used radio reception is impossible. You will not only get Droitwich or Pittsburgh or Paris—you will at the same time hear the transmitter in the vacuum-cleaner, which chances to have the same wave-length; but the programmes will be highly undesirable, for it will broadcast nothing but howls and rattling noises. The apparatus must be fitted with an interference-eliminator—it must be prevented from oscillating, from radiating.

Transmitter and Receiver

We have anticipated a little, which we really ought not to do in writing of scientific subjects. The orthodox reader of a scientific treatise will believe nothing that has not been explained to him in the course of his reading. To begin with, he will doubt whether radio reception or wireless telegraphy are in any way possible; he will rightly object that although we have described a transmitter which sends an alternating electric field out into the ether, a succession of hurrying waves, this transmitter scatters its energy heedlessly in space. Even if it should drive 150 kilowatts into its aerial, only a tiny fraction of this energy would be perceptible at any great distance, since

this energy, at first penned up and compressed in the antenna, is then distributed over the whole of the globe. And secondly, he will say: The waves of the Berlin transmitter (for instance) have a frequency of 841,000 oscillations per second. What telephone or loud-speaker can vibrate as rapidly as this? And if it could, our ears would know nothing of it, since our auditory apparatus is sensitive only to waves whose frequency is between 16 and 20,000 oscillations per second. No, says the orthodox reader—broadcasting is impossible!

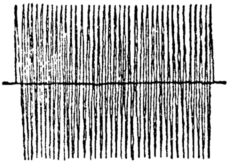
I might object that the loud-speaker on my desk is making itself heard at this very moment; but that is not evidence. Let us rather consider the transmitter which has just been described: and now let us assume that the engineer, feeling bored, begins capriciously to interrupt the transmitting current; playing with the contact-lever of the switch, in a changing rhythm—perhaps thus: Long—long—short. And the consequence? There will be no smooth, unbroken procession of waves; in their stead the antenna will send out sudden trains—no, bursts of waves; groups of waves—long, long, short. An old telegraphist, hearing this signal—long, long, short—will involuntarily think of "g"—the Morse sign for the letter g. So here, we see, is a possible method of wireless telegraphy.

Secondly: The strength of the transmitter-current is varied *periodically*. You remember, the grid controls the strength of the current. If we send an alternating current into the grid of a triode valve, the main current varies in time with the varying tension. And if, for example, we talk into a microphone, and send the alternating current of the microphone into the grid of a valve, the strength of the main current will vary in the same rhythm as the speech-vibrations. This means that the energy which the aerial radiates into space, the energy of the field, and therefore the amplitude of the waves, varies in the rhythm of the speech-vibrations. And so this is what the waves look like: The high-frequency waves are the *carriers* of the speech-waves; or, as we say, they are *modulated* by the latter. This is the principle of the broadcast transmitter.

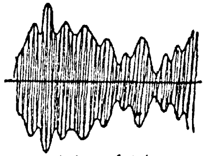
The hypothesis has been suggested that the butterflies radiate and receive short electric waves by means of their antennae, and so manage to understand one another. We are

not butterflies, and we know nothing of the electrical storms that go rushing through the atmosphere, unless we provide ourselves with a complicated apparatus.

To begin with, we fix up an aerial in which *all* the alternating fields that go rushing by excite little oscillations—whether they come from Berlin, Paris, London, the Sun, or the nearest vacuum-cleaner. The oscillations of an aerial seem perfectly bewildering; but the wire takes the matter calmly, and faithfully forwards the impulses received. Forwards them whither? Naturally, to an oscillatory circuit. For nothing material could contrive to vibrate in sympathy with the tremendous tempo of the Berlin broadcasting-waves—841,000 times a second. Only electricity can do such a thing. And we turn the knob of the variable condenser in the radio receiver —that is, we alter the individual tempo of the oscillatory circuit until it also is ready to oscillate 841,000 times a second. We have attuned or "tuned in" the circuit to the transmitter; they are both in resonance, oscillating with the same rhythm.


Carrier Waves


Current in Microphone

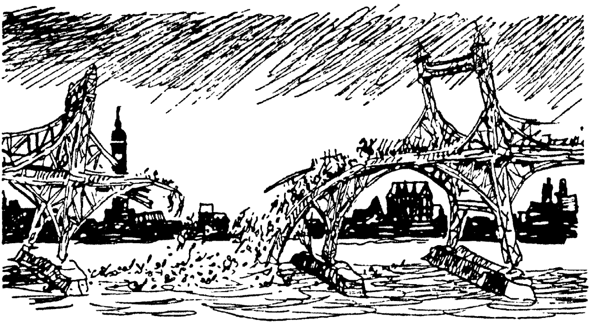

Modulated Waves

A company of soldiers comes marching over a long iron bridge. The heavy boots keep time on the causeway; the bridge begins to quiver slightly, and the quivering increases. Very gently the great girders begin to oscillate; this amuses the men, and they wilfully stamp harder; the synchronous oscillation of the bridge becomes more and more perceptible; now it increases to an uncanny degree, and the girders creak and groan. "The bridge!" someone cries in terror. It is too late—with a crash the girders tear themselves asunder, and fall, with the men, into the eddying flood.

It is a fixed regulation that large bodies of troops must break step on crossing a bridge, in order to avoid such a catastrophe, which is due simply to resonance. The marching

tempo of the soldiers happened to coincide with the individual rhythm of the bridge, so that every fresh step fell at exactly the right moment to communicate a fresh impulse. So the bridge gradually oscillated more and more violently, at last with destructive effect.

The problem of averting oscillation is of critical importance in engineering. Everyone knows, for example, how when the revolutions of the motor of an automobile have reached a certain figure the whole vehicle may begin to clatter. The revolutions of the engine have become exactly attuned to the

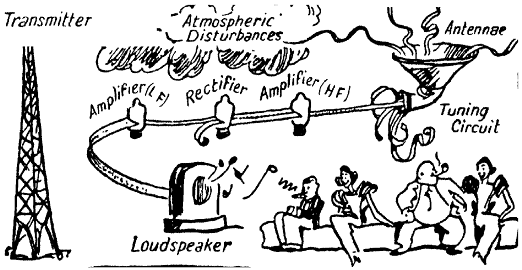


individual oscillations of the car; presently, when the frequency of the revolutions has increased, the car runs more smoothly again. The critical rate of revolution has been passed. Steel axles may break like glass; whole buildings may be destroyed in this manner. Wherever it can, engineering technique fights the enemy: resonance.

The radio engineer, however, does not avoid resonance; on the contrary, for only if resonance occurs can the tuned circuit break into oscillation when a perceptible current is applied. But the back-coupling of which we have already spoken is of course a resonance phenomenon.

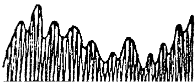
The waves radiated through space from Berlin are absorbed by the tuned circuit, and now it participates in all the vicissitudes of the waves. In the tuned circuit and the last circuit of the transmitter precisely the same things are happening. But we must not forget—the oscillations of the transmitter have been

modulated. The tuned circuit is pulsing with a tempo of 841 kilocycles, whose strength varies with the rhythm of the speech-vibrations of the transmitter. (See the sketch on p. 127.)



The oscillations could be reinforced in the usual way by a triode valve; but this is never done; they are sent on.

And now for the essential secret of the radio receiver: These modulated waves are passed on to a *detector* or *rectifier* valve, which will pass currents only in one direction. It cuts off half the alternating current, and discards it. And so the waves which are delivered by this rectifier assume the form of a pulsating direct current. Now this current is reinforced or *amplified*—once or perhaps twice—and at last it is strong enough to move the diaphragm of a loud-speaker. But the diaphragm, an inert sheet of iron, or a cone of paper, feels nothing of the quick variations of the high-frequency (radio frequency) waves; it obeys only the coarse and emphatic oscillations. The loud-speaker vibrates in time with the rhythm of the speech-current (audio-frequency), of the microphone. We hear, in London, what was sung or spoken in Berlin.



Rectified Waves

Current in Loud-Speaker

But what about the Chinese?—Well, the electric waves, whether modulated or not, have a fixed rate of travel: 300,000 kilometres per second. They travel from Shingleton-on-Sea, where the band was playing at the beginning of this

chapter, to China, in less than one-thirtieth of a second, and the complicated processes in the transmitter and the receiver are completed almost instantaneously—thanks to the slight inertia of electricity. But the sound, with its velocity of 330 metres a second, takes one-third of a second to travel from the bandstand to the chairs, a hundred yards distant, on which the two men, the fat and the thin, are still arguing. It takes longer than the broadcast waves take to reach China!

PART THREE

LIGHT-WAVES

LIGHT-WAVES

Electro-Magnetic Waves

THEY are busy today in the transmitting station. A new man has received permission to try out a new sort of transmitting valve which, if what he says is true, will make it possible to alter the wave-length at will. Now he is standing before the switchboard; a red control-light flashes and goes out again, and with a quick, energetic movement he throws in the switch. The transmitter begins to radiate. Slowly and imperceptibly the new engineer turns the knob of the condenser. The wave-length sinks—it was 575 metres to begin with. Now it falls to 100, and then to 30 metres—and the short-wave amateurs in America begin to listen in. A new short-wave transmitter, unknown to them, has begun to broadcast! But the man in the white overall is not yet content. The frequency-meter over which he is bending with a tense, listening expression shows a reading of 300,000 kilocycles—1 metre wave-length. This both he and others have obtained before—but now the new circuit begins to operate. Steadily and resolutely he turns the shining vulcanite disks—10 centimetres, 1 centimetre, 1 millimetre. And still the wave-length decreases. The grey-haired machinist puts his hands to his head—he feels a superfluous stranger in the familiar transmission-hall. Uneasy and irritable, he steps out into the courtyard and casts an inquiring glance at the aerial. He feels quite hot with anger, and wipes the perspiration from his forehead. But no—it is as hot as ever. It is March—it cannot really be so hot?—but there is no doubt about it—an impossible heat is radiating from the aerial! "Hi!" he shouts, "stop that! You are overloading the transmitter!" But the engineer behind the window-pane silently shakes his head. Now the wave-length is only a tenth of a millimetre. We call such radiations heat-rays—for the nerves of our skin react to electro-magnetic waves of this length. The heat-rays are electrical waves of 100–1 μ (the symbol μ stands for a thousandth of a millimetre). A kitchen stove is an electrical transmitter! And he turns the knobs farther—but only just a little. The

aerial is beginning to glow. It is a deep, hardly perceptible red—but there is no doubt whatever that it *is* red. Between 7 and 8 ten-thousandths of a millimetre the heat rays gradually become *visible*. Now the wave-length-meter reads 0·6 μ—a full, bright red shines from the aerial—a great beacon burns above the city, and the houses are flooded with a faint blood-red radiance. The transmitting station is aglow, and the red grows brighter, passing into orange, yellow, green, blue, and violet—and the violet fades and disappears. 0·72 μ to 0·397 μ were the readings on the engineer's wave-length meter. Electrical waves between these wave-lengths are visible to the eye—we call them *light*. And if the wave-length becomes still shorter we have the ultra-violet light of the mercury-vapour lamp, and finally the Röntgen-rays—and if the transmitter were to radiate these all the people in the neighbourhood would become transparent to them, and if they were photographed they would look like so many skeletons walking the streets. One cannot go much farther. The γ-rays come next, the rays which are emitted by the radio-active elements, and the "cosmic rays" close the series, with a wave-length of less than 1 billionth of a millimetre. The engineer switches off the current.

He has passed the whole family of electromagnetic waves in review. They were all of essentially the same character—they differed only in wave-length. And our eye—the engineer reflects—is nothing more or less than a receiving set. A radio receiver, which is restricted to the ridiculously short band of wave-lengths—0·7 μ to 0·4 μ. Any ordinary wireless receiver covers a larger gamut. Still,

it suffices us. All the same—thinks the engineer—it is a pity that the eye is restricted to this short band of wave-lengths. How much more rapidly scientific research might have progressed; how much earlier we should have recognized the fact that light and electro-magnetism are one and the same; how many false paths and blind alleys we should have avoided! —But he suddenly remembers an old acquaintance of his who earlier in the day wanted to borrow yet more money from him. "I haven't the money on me," he said. But if his friend had had Röntgen eyes he would have seen the coins in his left-hand trousers pocket. No, he thinks to himself, it is just as well that the human eye cannot see anything under $0 \cdot 4\ \mu$!

Alas! this engineer, this obliging fellow in the white overall, has as yet no counterpart in reality. Even with the aid of the most ingeniously constructed circuits, our radio transmitters cannot go below wave-lengths of a few centimetres. But Mrs. L. Arkadievna, by inducing small sparks from particles of metal in petroleum, has generated electrical waves of $0 \cdot 2$ millimetres in length, which must be counted as heat waves, and has thereby filled a long-vacant gap. And perhaps this young man who, with an ironical bow, has just taken leave of the still exasperated machinist, will one day be a reality.

We know today that light is an electro-magnetic oscillation, a vibration of the ether, a wave-motion, whose wave-lengths lie between $0 \cdot 7\ \mu$ and $0 \cdot 4\ \mu$. Thanks to the theory of electricity we have made the acquaintance of the *ether*, the seat of the electro-magnetic field.

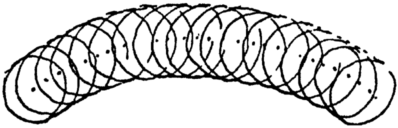
But in the year 1650, when Huygens first evolved the wave-theory of light, no one had as yet any notion of an electric field. People did, of course, know that the sun shines and that light comes to us out of space.

At all events, then, some sort of medium had to be presupposed in which the light-waves could travel—a *luminiferous ether*, filling empty space.

Such a notion, of course, is not without its intellectual difficulties; but these difficulties were avoided by Newton's theory of light. According to Newton's theory, a luminous body flings off tiny corpuscles of light; in other words, light is atomic in character, and a ray of light consists of a stream of

light-particles, just as an electric current is a stream of electrons; a sufficiently attractive conception, but one which in the end proved untenable. Let us see what Huygens thought about the matter.

A stone falls into water, rudely shattering the calm of the mirror-like surface. A single point is suddenly roused from rest; and now Huygens logically develops the conception of the field. A point, a particle of water, is subjected to disturbance —and since it does not exist in "splendid isolation," alone in space, but for better or worse is allied to its neighbour-particles, it communicates the disturbance to them. Just as a rumour, an item of scandal, is passed from mouth to mouth—just as every respectable citizen, in his annoyance at being disturbed,



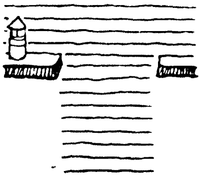
is obliged to unbosom himself of the scandal before he can recover his usual tranquillity, and accordingly repeats it to his circle of acquaintances—so the particle of water which is affected by the disturbance begins to oscillate, and thereby becomes the starting-point of a little circular wave. All these new—secondary—circular waves produce a combined effect —working together, they generate, in the rest of the community, the wide, ever-expanding circle which travels over the whole pond. Here, you see, is a case of transmitted action! And it was just in this way that Huygens explained the waves of light: Each point affected by the light-stimulus begins to oscillate, becomes the starting-point of a little spherical wave, transmits its stimulus to its neighbours, and returns to rest.

A rectilinear wave-front is obtained if we plunge a ruler into the water, disturbing a number of points simultaneously. But we can also regard the rectilinear wave as simply a small segment of a very large circle. We call Oxford Street or Broadway or Friedrichstrasse rectilinear—yet each is only a segment of a great circle—the circumference of the Earth.

With a long, straight front the waves of the ocean roll against

the shore. Always in the same tempo, with a straight front they travel over the wide blue sea and subside on the yellow sand. And so, following a rectilinear path, always keeping time, light travels through space.—And now the water-waves beat against a breakwater in which there is a gap; they run unhindered through the gap, and there we have a "beam" of waves; but on either side of the "beam" the water is undisturbed—for it lies in the "shadow" of the breakwater.

So we see—there are really no such things as *rays* of light; they are an invention of the theorist, a fiction. But if there are no such things as rays of light, what are there?—There are more or less tiny *bundles of waves*—or "pencils" of light. This must be most distinctly emphasized: The only physical realities are the wave-fronts; and we shall bear these in mind when for the sake of convenience we speak of light-rays—understanding thereby a sufficiently slender bundle of waves.



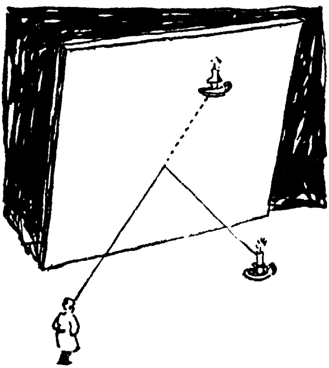
Everybody has observed the rectilinear propagation of light. When the sun shines into a smoky room we see broad, straight beams of light, in which the particles of smoke and dust are dancing. When the sun shines through a gap in the clouds we see the light pouring down upon the earth in straight, clearly defined shafts or bundles. Since our earliest childhood we have been aware that light travels in straight lines. We have become so accustomed to the fact that a man whom we *see* in front of us is really there, and not standing at our elbow; that even we enlightened Europeans—to say nothing of the African negroes—would feel abominably deceived if a magician were to revolutionize this state of affairs.

Reflected Images

Nevertheless, we need not look far for such a magician. For the magician's name is—the mirror. The mirror diverts the light-rays from their original direction. If it is clear enough, anyone will really believe that his friend—the mirrored image —is standing behind the mirror. We think to find him straight

before us—in the direction from which the light-rays are coming. And the suspicious savage will walk round the mirror once or twice before he allows himself to be convinced that there is really no one behind it.—With the aid of Huygen's wave-theory the laws of reflection can readily be deduced—and also the well-known law that the angles of incidence and reflection are equal.

Newton, however, had a still simpler explanation. Reflection means the rebound of the light-particles from the rigid wall of the mirror. Everybody who has ever played with a ball knows that an elastic ball is reflected symmetrically.



The wave-theory explains also how it is that two people can see each other simultaneously in the same mirror—and why a number of images can be seen at the same time in the same mirror. Many years ago there was a perfectly serious discussion in a German periodical as to where the images in a mirror are really situated. What is *really* in the looking-glass—the question was asked—my image, or yours, or that of the room, or all of them together?

The people who started this discussion were not only ignorant of the laws of physics—they were also intellectually lazy, and they adhered too persistently to primitive conceptions.

You can generate ripples in a washhand-basin, and you will see how they are reflected from the sides of the basin; and you will see also that several trains of waves can run right across one another without disturbing one another in the least. It is the same with light-waves. Two rays of light can cut and penetrate each other without the slightest mutual disturbance. For example, if we make the beams of a green and a red searchlight cross each other, the two beams merely pass through

each other, and the red beam is still just as red as before; it has not acquired the faintest trace of green. Light cannot lose its colour!

It is the same with reflected images. Of course, a vast multiplicity of light-rays is falling on the mirror, and leaving it at any moment; but the same condition of affairs occurs everywhere, and if I merely glance across the street at the shop-fronts the space outside is traversed by so many light-rays of such different categories that it is impossible to form any conception of the state of the ether at this point. It is like an ocean upon which hurricanes are descending from all sides at once. But as I have said—waves and light cannot lose their colour, and each individual ray of light escapes from the confusion whole and uninjured. One might feel inclined to ask why we notice no symptoms of this congestion; why in spite of this anarchy in the ether we still get a clear image. (And some such question, perhaps, was at the bottom of the mirror controversy.) The answer is simple: we *see* only the light-rays that strike upon our eyes; others have no existence for us. You and I can never see the same ray of light!

Why do not rough surfaces—say a woolly carpet or a wooden plank—reflect the light? Well, they do reflect the light, and throw it back into our eyes; otherwise we could not see them. But they reflect it in all directions; they give a confused, dispersed, "diffuse" reflection. Isn't this a violation of the law of reflection?

Reflection is, of course, always symmetrical. There is no exception to this law. But a plank, a carpet, a rug is not a *flat* surface, in the optical sense. Like the surface of the Earth, the surfaces of such objects are covered with thousands of valleys, mountains, and crevices. Mountains and valleys which are minute according to our standards, but gigantic in comparison with a light-wave. Every part of a thick pencil of light strikes on a differently inclined portion of the table or carpet, and is reflected—somewhither—in accordance with the angle of incidence—always in strict obedience to the laws of reflection!

In the case of reflection by a mirror the pencil of light is just as straight and compact after reversal as before. It is like

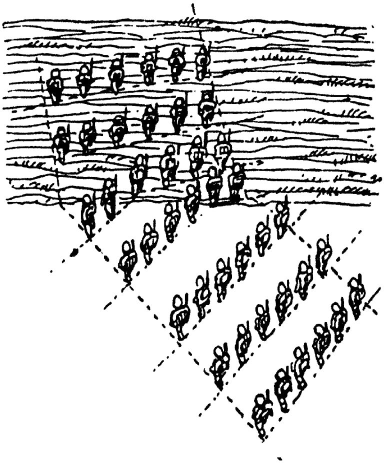
a marching column of soldiers or sailors, proceeding in rigid order through the principal streets of a city. Those who do not cross their route are not aware of their presence. But by diffuse reflection their discipline is dissolved. The table gives the order: "Break ranks!"—the rigid formation dissolves, and the soldiers disperse all over the city—which now, for the first time, becomes really conscious of their presence. If you plane the table, smooth it with glass-paper, and fill all rugosities with a smooth layer of French polish, it will "shine like a mirror," and it will now reflect, as an "optically plane surface," almost as faithfully as a plate of glass.

But we will leave the polishing to the cabinet-maker, and rejoice that there are so few mirror-like objects in the world. Without diffuse reflection the world would be dismal, colourless, and empty. We should see nothing at all—for we don't see a mirror! We see *in* it, through its mediation, the "source of light," using the term in its widest acceptation—for example, your friend, or a new hat. For the most delicate optical experiments very carefully polished mirrors or prisms are made of specially selected, absolutely flawless glass, which is cooled over a period of months or even years, so that no internal strains shall develop. Such glass is optically empty—that is, colourless and invisible. And in a perfectly reflecting world we should alternate between absolute dazzlement and pitch-black night—never seeing anything but the sun or stars or lamps—the only primary sources of light. It would be intolerable.

Refraction

Reflection is the first queer experience which a ray of light may encounter on its journey through the Universe. But now comes the second: *refraction.* A stick, or a pencil, partly immersed in water, looks *crooked*—so the light, we are obliged to conclude, does not leave the water for the air without distortion. Something has happened to it. That this happens at the boundary of the two substances will not surprise a modern thinker. There is always something unsettled and strange

about a boundary—in physics as in life.—We will send for our column of soldiers again, and let them march, in orderly ranks, obliquely across a meadow and on to a patch of ploughed land. On the ploughed field they will march more slowly than on the meadow, so that the right-hand file-leader will be the first to fall a little behind; then the man on his left, and then the man on *his* left, and so on—and in the end the direction of march will have been deflected. It has been bent aside at the boundary. For the same reason the pencil appears bent. Our eye deceives us—it declares that it sees something where there is really nothing to see. The eye is a creature of habit. If we had had more to do with refracting surfaces we should probably not be subject to this delusion. A man who from childhood had always been given crooked pencils, and who could instantly convince himself of the contrary by the sense of touch, would probably come, in the end, to regard the pencil as straight. He would be living in a different world.—To put it once more into words: Light, on passing from a rarer medium to a denser, is *refracted*—diverted—and always towards the "angle of incidence." The greater the "bend," the greater the refracting power, the *refractive index*, of the substance.



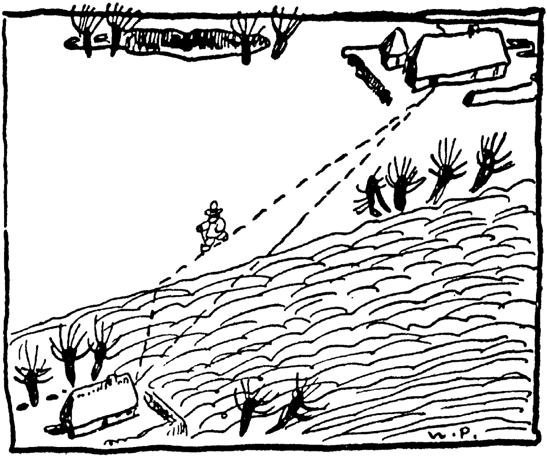
The expression "denser" calls for some explanation. It means, of course, optically denser—denser for light. Substances which are light in the ordinary sense of the word may quite well be extremely dense in the optical sense, and possess a high refractive index. And two substances with the same refractive index cannot be distinguished by optical means. If you drop

a diamond into a solution of carbon disulphide it disappears —becomes invisible. Both substances have the same refractive index.—But we have just made an assertion which we cannot conscientiously defend. We have forgotten absorption. All substances swallow up—absorb—a little light; some more, some less. The greater the "coefficient of absorption," the greater the percentage of light absorbed; we must bear this in mind. If a man could assume the same refractive index and the same coefficient of absorption as the air, he would be invisible —but if he were to go bathing you could detect him at once in the water.

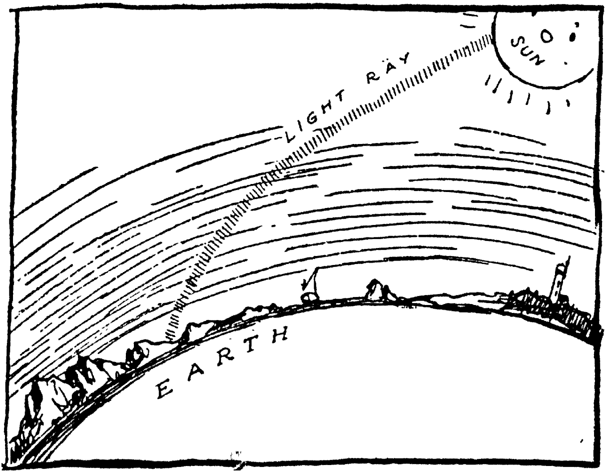
Let us treat the example of the marching files of soldiers as we should treat a lemon—squeeze it until we have extracted from it the last drop of physical knowledge, which is this: On ploughed land a man travels more slowly than across a meadow. In a substance with a *greater* refractive index the light travels *more slowly*; the refractive index is merely the ratio of the velocities of light in the two contiguous substances. Retardation occurs because in the denser medium the light takes shorter steps—that is, its wave-lengths are shortened; not because it oscillates more slowly (see p. 111, *Waves*). And we know that the frequency of light, its number of oscillations per second, remains the same all its life long; it is a fundamental property of light. For historical reasons, unfortunately, it is the wave-length of light that has always occupied the foreground. We must remember this in future when we hear the word "wave-length" spoken.

Time is Money

Of light a general principle holds good, a sort of categorical imperative; it was discovered in the seventeenth century by Fermat. It might be called "the principle of the hurrying light-ray," and it may be expressed thus: "Whatever you have to do, follow such a course that you do it in the shortest possible time." By means of this principle the refraction of light can readily be explained. A man who has to run as quickly as possible from a point in a meadow to a point in a ploughed field will keep in the meadow as long as possible, and will



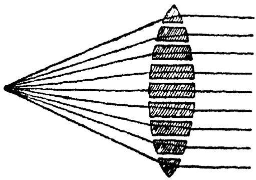
walk only a little way over the ploughland; so that the path which leads him most rapidly to his goal will be a crooked line. We may question whether an ordinary light-ray possesses much intelligence, or understands the meaning of the cate-



gorical imperative. But it need not waste any time in thinking about the principle; for this principle is a matter of course. A light-ray travels from the Sun to the Earth, and passes through the atmosphere. But since the air becomes *denser* near the Earth, its refractive power increases, and the light travels more slowly; the upper part of each wave-front overtakes the lower; the light-ray bends downwards. It cannot do anything else; for we must not forget that there is really no such thing as a ray of light; there are only more or less slender pencils of rays. But it looks as though the light-ray, obeying Fermat's categorical imperative, had remained as long as possible in the upper strata of the atmosphere, where it can travel more swiftly.—So much for the principle of hurrying light, which is yet another consequence of the wave-theory. It suffices, as I have said, to explain all the phenomena of optics—reflection, for example; and later on it will help us to arrive at quite surprising conclusions.

Practice after Theory: Lenses

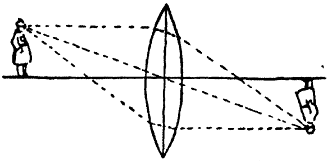
How a lens works you will see in the accompanying sketch. Nothing more need be said. It combines parallel light-rays at a point which we call the *focus* or *focal point*, which means "burning-point." (If you have ever lit paper or grass with a "burning-glass" you will know why.) We call a lens which collects rays in this way a *condensing* lens—in this case a bi-convex lens, because it has two convex surfaces.



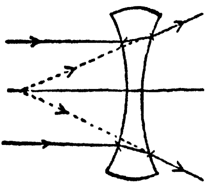
Now read the sketch from left to right, and you will see that the light which proceeds from a luminous point at the focus of the condensing lens is parallel after it has passed through the lens.

The next sketch shows how a condensing lens casts an image of an object which is not at an infinite distance (that is, which does not emit parallel rays of light). Here the light-rays proceeding from a man are united again behind the lens. Of

course, the lens does not know that the man in front of it constitutes an indivisible unity; it makes separate images, collecting the light-rays from every point, from head and body and feet, and combines them in a plane, the *focal* or *visual plane*. That all the points of the image fall in the same plane, and in their proper place, is due merely to its regular formation. It throws an image, a "real" image, which you can catch on the ground-glass focussing-screen of your camera. The closer the man approaches the lens, the farther the image recedes from it, and the larger it becomes—and the farther we must rack the focussing-screen from the lens.



Condensing-lenses are honest. Now for the swindlers—the dispersing lenses. Here is a "biconcave" lens—and you see how it disperses the light-rays into space. Our eyes readily allow themselves to be deceived; naively and childishly, they believe in the rectilinear propagation of light, and mentally prolong the rays that reach them. They think they see an image—a "virtual" image, we call it—which really doesn't exist: an image that cannot be caught on a focussing-screen, but which would—if it really existed—send out exactly the same rays as those which the lens transmits.



A condensing lens also can produce a virtual image—if the object is nearer to the lens than its focal point. In this case divergent rays are transmitted, which here again are interpreted by the eye as the rays from a virtual image. A magnifying-glass produces such an image.

The many kinds of optical instruments which we know all depend on these principles—for example, the telescope, with its large condensing lens, the "objective" or "object-glass," throws a small inverted image of distant objects, which can then be magnified by another lens or lenses. The prismatic

field-glass acts in the same way, only here the image is reversed again by two prisms, so that it appears the right way up.—But this, of course, is only a greatly simplified summary of optics.

In a bad telescope you see everything surrounded with a brilliantly coloured blue and red fringe. This is due to the *chromatic aberration* of the lenses; it is explained by the fact that the lens does not treat blue and red light in exactly the same way. The defect can be cured if we replace the single lens by two lenses of different kinds of glass, cemented together, so that they act like a single lens, only the second lens reverses the chromatic dispersion of the first. This is known as an *achromatic objective*; but only the chromatic aberration is remedied by this means.

There are still other defects or aberrations, as any photographer knows. An ordinary lens is not a careful artist; the image which it throws of a point is a tiny line. We say that it is "not point-like" (a-stigmatic, astigmatic). The lens, so to speak, adds something of itself; it distorts, as a bad loud-speaker will distort music. The bigger the lens, the more it is filled to the very edge with light, the greater the defect.

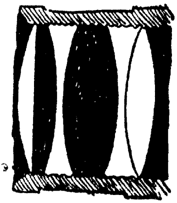
Now the theoretical optician has to get to work. He has to calculate systems of lenses—whole series of lenses—which mutually cancel out their defects; they must be *an-astigmatic*—that is, they must form images which consist of points. They must throw an image which is sharp to the very edge, and yet at the same time they must let through as much light as possible—must have as large an "aperture" as possible. Lastly, they must not be too expensive, so the optician will not use more lenses than are absolutely necessary.

The calculation of lenses is a very difficult art, and it is always entrusted to people who have great experience in this special department of optics. The lens must then be ground and polished to exactly the calculated form—again, a task that calls for lifelong experience, for even to this day the final polishing depends on the tactile delicacy of the polisher.

In a "Sonnar" lens, to take an example—a modern, ultra-rapid photographic objective—the system consists of seven lenses. Its aperture is $1 \cdot 5 f$—that is, for a focus of $7 \cdot 5$ centi-

metres its diameter is 5 centimetres. And the sketch on this page shows a very famous objective, one of the earliest and best anastigmats, a "Zeiss Tessar," which, as you see, consists of four lenses.

The eye contains a lens which throws a real, inverted, diminished image of the outer world on to the retina. How comes it that we see things the right way up? The question is often asked—but it is wrongly expressed. Light-waves fall on the retina and communicate nervous stimuli, which are communicated to the brain, which has the task of forming a picture of the outer world from the increasing signals—just as the Morse telegraphist has to interpret the incoming dots and dashes in plain English. How the brain sets about this translation we do not know. But we do know that children must gradually learn to see. The sense of touch, sensations of warmth, and indeed all the senses help in this first process of finding one's bearings. All together finally furnish the picture which we form of the outer world—and which is known to us alone! I cannot even say whether your picture is the same as mine. That we use the same words to describe it means nothing. And why should this picture, which comes into existence in the brain, be "upside down?" It is not easy even to say what is meant by such an expression. There is an intellectual error in the form of the question; we speak as though the brain had yet another pair of eyes, with which it gazes at the little image in the retina.



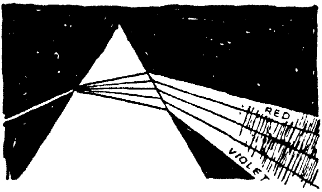
That the brain does possess an extraordinary power of inversion is proved by the experiment of an American psychologist, who put on a pair of spectacles fitted with inverting prisms, which really showed him a world standing on its head—since it deranged the lifelong co-operation of the senses. At first his brain was disconcerted by this strange picture of the world. Every step, every movement of his hands called for consideration and intellectual effort. But after a few days the brain had transposed itself, and the man no longer saw anything extraordinary in the world before his eyes—it seemed to

him "the right way up!" And if he had worn such spectacles from birth, it would never have occurred to him that his picture of the world was in any way unusual. But when he stopped wearing the spectacles—then, to his unspeakable astonishment, it once more took him some days to find his bearings, to see things "the right way up!" He stumbled about and collided with things until his brain was once more accustomed to normal vision!

Colour

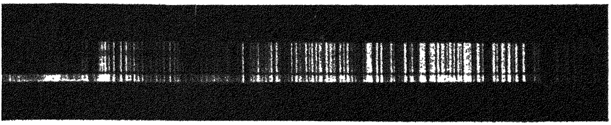
In London there are people who follow the peculiar profession of "tea-taster." They are people whose faculty of taste is so highly developed that they can immediately "taste out" the individual varieties of tea in a blend of teas. The optical "tea-tasters" are the spectroscopists. They determine what wave-lengths, what sorts of light, are present in a ray of light. Their ancestor was Newton—the first to analyse sunlight.

Sunlight is white light—that is surely simple enough? How can white light, the simplest kind of light, be a compound? But Newton placed a prism, a triangular piece of glass, in the path of a ray of sunlight—and he saw, to his astonishment, that the white light was spread out into a coloured band. White light is not homogeneous; it is made up of rays of different colours—the well-known colours of the rainbow, from red to violet. The red is bent aside through the smallest angle, the violet through the largest. How are we to explain this?



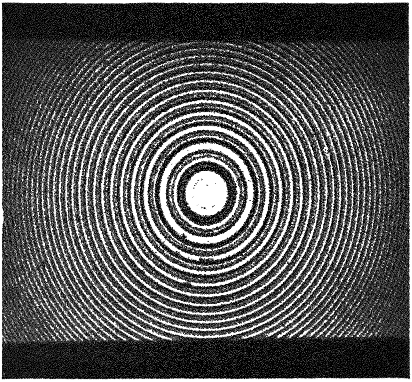
Let us go back to our soldiers, and mix them with boy scouts—with youngsters whose stride is perceptibly shorter. In the meadow they all march at the same pace; the scouts have to move their legs a little quicker. But when they come to the ploughed land they feel the additional effort more than the soldiers, and so their involuntary deviation is greater.

PLATE 3



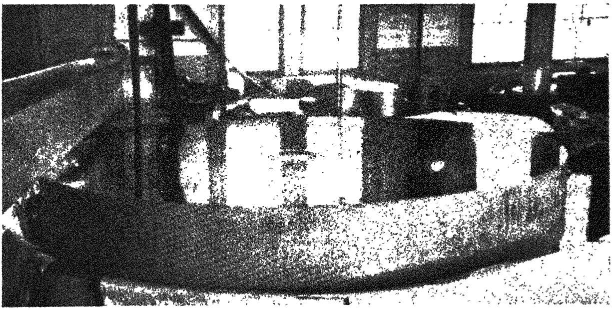
Haspas

PRISMATIC SPECTRUM OF RADIANT IRON VAPOUR



Karlson

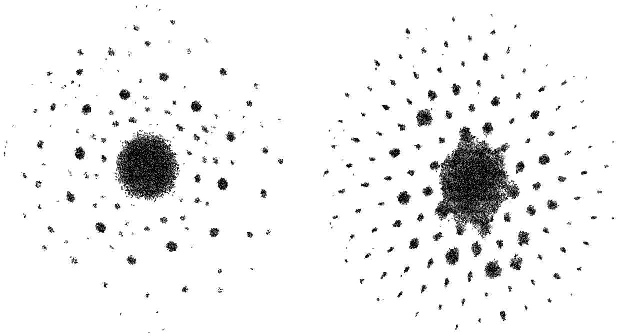
EXTREMELY FINE STRUCTURE OF SODIUM LINES
(AS SEEN IN INTERFEROMETER)



Wide World

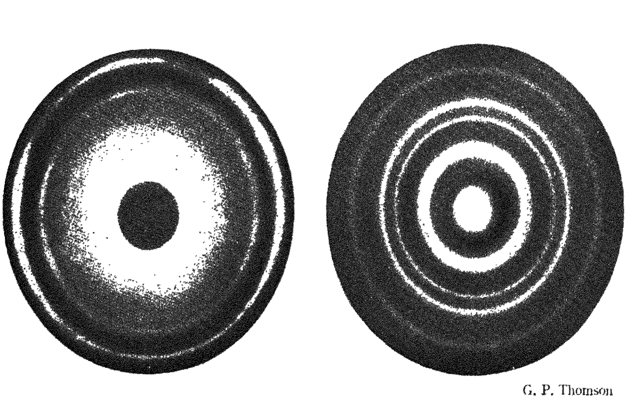
GLASS DISK FOR THE 5-METRE SPECULUM OF THE TELESCOPE NOW BEING BUILT FOR THE MT. WILSON OBSERVATORY

PLATE 4



Rupp

DIAGRAMS OF IRRADIATION THROUGH A CRYSTAL: LEFT, WITH RÖNTGEN-RAYS; RIGHT, WITH ELECTRONS

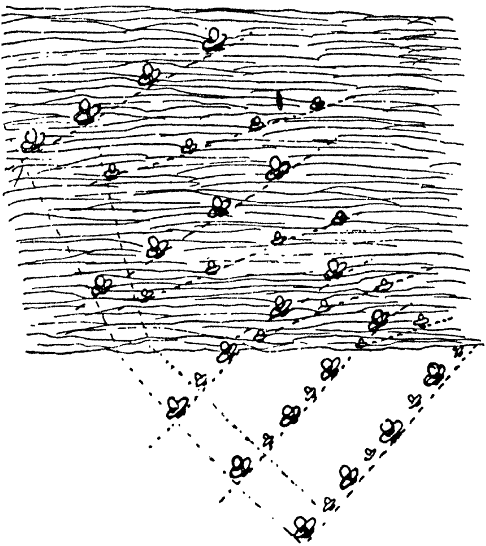


G. P. Thomson

DIFFRACTION FIGURES OBTAINED ON THE IRRADIATION OF METALLIC FOIL: LEFT, WITH RÖNTGEN-RAYS; RIGHT, WITH ELECTRONS

ELECTRONIC WAVES

Once they have crossed the boundary they march pluckily on —but in a different direction. The scouts' direction of march is bent through a greater angle at the boundary than that of the tall long-legged soldiers. Shorter steps—shorter wave-lengths, if we are thinking of light. Short light-waves, therefore, are refracted more strongly than long. By means of refraction we can spread light out in order of its wave-lengths, and the



conclusion to be drawn is obvious: red light has a greater wave-length than violet. And it has.

The colour of light depends solely on its wave-length. Colour and wave-length mean the same thing—except that colour is a psychological, visual, qualitative conception, an experience, whereas wave-length is an exact, physically measurable magnitude. Wherever in the Universe an oscillation of wave-length $0{\cdot}42\,\mu$ strikes upon our eyes, our brain will register the impression "violet." When we find an electromagnetic oscillation with a wave-length of $0{\cdot}65\,\mu$ we call it "red," since it appears so to our eyes. It does not matter where

the oscillation originates—whether from the setting Sun, or a dark-room lantern, or the overloaded aerial of our fairy-tale. We do not ask to know the origin of the waves—only whether they are of the prescribed size—that is, wave-length. Huygens was responsible for this idea—and a magnificent idea it is. It was this that enabled spectroscopy to evolve into an exact science. Lord Kelvin said in respect of any phenomenon: If you can specify a measurement, a number, then you know something about it; if you cannot, your knowledge is defective and unsatisfying. The knowledge that the different colours are only psychological interpretations of the different wave-lengths is fundamental, and furnishes the quantitative data.

White light is a crazy medley of many wave-lengths—and conversely, a mixture of the colours of the rainbow gives what our eyes perceive as "white light." Such a mixture is made by the chromatic spinning-top, on whose disk the seven colours are painted like the segments of a tart; when the top spins so rapidly that the impressions of the individual sections melt into one another the colours are blended in a whitish disk.

How is it that the world is so many-coloured? This, too, depends on the wave-lengths of light. A green counterpane—a brilliant painting—a red apple—all wait for their cue. The molecules of the apple-rind swallow, on principle, all the light that falls upon them, excepting only red light—waves of $0 \cdot 65\mu$—which they forward elsewhere. Whatever assails them, they repeat always the same note—red, red, red. The splendour of colour is all borrowed finery. Take the apple into the red-lighted dark-room.—Naturally, it is still red. But the green counterpane will look black there. Obviously, it is accustomed to pass on green light; but red, blue, yellow—all other light, in short—it swallows. And here in the dark-room it waits in vain for its cue—green. So it is silent and abashed. Throw what light you like upon it—until there is green in this light the counterpane will never look green to us. Borrowed finery, nothing more!

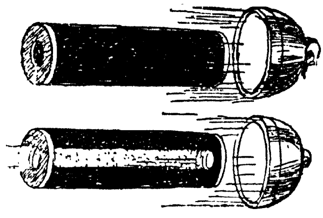
In practice, of course, many colours are more or less "broken" or impure. The majority of substances are not strictly "monochromatic." They do not absorb *all* the light

that does not suit their purpose. The counterpane reflects traces of red, yellow, and blue as well as green; we have to deal, almost always, not with physically pure colours, but with mixtures of colours.

Why is the Sky blue?

The answer is as follows: No one, since the beginning of the world, has had a side view of a light-ray.

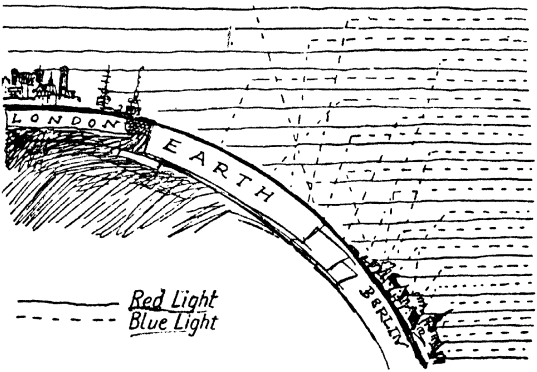
If we send a ray of light through an empty, completely dustless glass box, it looks, if we observe it from one side, absolutely dark; it is "optically void." It might be traversed by the light of a million candle-power searchlight, but we should notice nothing—any more than we can tell by looking at a transmission-cable whether or not it is carrying a current. Blow a mouthful of tobacco-smoke into the box, and at once a dazzling white cylinder detaches itself from the dark background. The light is bent aside, dispersed, by the innumerable, eddying particles of dust and smoke, and this dispersed light enters our eyes; we see it. This is why it is light all day on the Earth. The light from the Sun, diverted and diffusely reflected, spreads itself abroad through the whole atmosphere. We know how waves are propagated on a smooth pond. But what if the surface of the pond is not smooth—if it is broken by rocks and boulders? Then, obviously, the waves will no longer follow a direct and unimpeded course. They will be turned aside by the rocks—diverted and dispersed. And we shall see that this dispersive effect will be closely dependent on the nature of the obstacles, and the length of the waves.



A matchbox, in a washhand basin, will impede and disperse the little circular waves. But if this same matchbox is floating in the Bay of Biscay, will the wide, majestic rollers be disturbed by the tiny object?—The longer the waves, the less are

they impeded and bent aside. And in the atmosphere there is matter enough to impede them. Particles of dust, water, and smoke, and all the tiny motes that move, in rapid zigzag motion, in a slanting ray of afternoon sunlight—all these turn the light aside, divert it from its direct path to our eye, and so become visible.—This is why we see a ray of light when cigarette-smoke is blown towards it.

Then air that is perfectly free of dust does not bend the



light?—Yes, it does. Its molecules are big enough to disperse the light in all directions if the wave-length is short enough—that is, if the light is blue or violet. Blue light is dispersed by the molecules of the air—red light hardly at all. A sky like that of the Moon, a sky without air, is perfectly dark and colourless. But air disperses light; even some of the sunlight that is really aimed at London reaches the eyes of the Germans in Berlin—mainly, of course, the blue, short-waved light. So this is why the sky is blue. The higher we climb the mountains, the clearer and less dusty the air, the less is the proportion of light dispersed, and the bluer its colour. In dull weather, on the other hand, when the atmosphere is overcharged with drops of water, water-vapour, and dust—that is, with *large* particles—not only the blue light is dispersed, but also green, yellow

and red light, whose rays are longer. The result is a dull, dirty grey mixture.

A man who disperses his possessions is soon impoverished. The sunlight, unsuspiciously and lavishly scattering its blue, is presently white no longer. If its path through the atmosphere is long enough—when the Sun is low in the evening—only the yellow and red rays, whose constitution is robust and long-waved, are still able to reach us. The blue has been given away *en route*. Hence the resplendent hues of the sunset. The haloes round the Sun and Moon, the occasional "mock-suns" or "sun-dogs" of the Arctic, are due to the same cause: the bending of the light by impeding particles. And the scientists will tell us why in foggy weather the headlights of a motor-vehicle are covered with a yellow disc. Yellow light consists of relatively long waves, and is not so bent and reflected as ordinary white light, which contains a great deal of blue.

The modern microscope makes ingenious use of the dispersion of light. We can see only objects which are at least as large as a wave-length—a few ten-thousandths of a millimetre. The modern microscope has reached this limit—which has been fixed by Nature—thanks to progress in the construction of lenses, and the methods of illumination. But very much smaller objects can perceptibly disperse the light. The ultra-microscope of Seidentopf and Zsigmondy takes advantage of this fact. The observer does not, as in other microscopes, direct a bright pencil of light into the objective—he lights the field of vision brilliantly from one side, so that the pencil of light shoots past the objective at right angles to the axis of vision. If we look through such a microscope we see nothing at all at first—merely darkness. And when the solution to be examined is brought into the field we see sudden, flashing sparks of light, so that the field is like a sky full of twinkling stars—and these are what we are looking for. In this way particles as little as a tenth of a wave-length in diameter can be detected. Their shape cannot be recognized; they are points of light, nothing more. But we can see that there is *something* there; and this is often important enough.

Dark Light

"Korff invents a day-night lamp, and when it is turned on even the brightest day is turned into night."

MORGENSTERN

Our investigation of the vicissitudes of light inevitably led us downwards to the tiny light-waves themselves. You will perhaps expect to learn that in the realm of these minute dimensions all sorts of surprises and curiosities emerge, and you will not be disappointed. The shortest formula we can find to express them is:

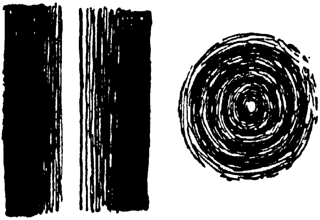
$$\text{Light} + \text{Light} = \text{Darkness.}$$

"M. Fresnel is a magician," wrote the great French physicist Poisson, about the year 1800.—Poisson was violently attacking the "absurd wave-theory of light."—"M. Augustine Fresnel declares that he can see round the corner. He has such good sight that if we place him in the shadow of an opaque screen he will still be able to see the lamp!" Poisson slapped his forehead in sheer amazement that apparently serious people like the highly-gifted Fresnel should support a theory which led to such nonsensical conclusions. What absurdities they believed!

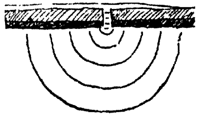
M. Poisson was not so far wrong, and he was much too good a physicist to make an assertion which could not be supported. We all know today, of course, that water-waves can to a certain extent circumvent a small obstacle. Then why cannot light-waves do the same?—Well, here is a photograph of the shadow of a small screen; in the middle of it there is light! Poisson—quite without intending it—had given the wave-theory a firm foundation; shortly after his onslaught the "bright shadow" of a small screen was detected.

The bright shadow and the dark light—it is easy enough to obtain them. You take two sheets of cardboard and gradually bring them together until only a narrow chink is left between them. Look through this crack towards the lamp—it is now a chink of light. The sheets of cardboard are brought still closer together, until the chink is all but closed—and until it is quite

closed. And just before it is quite closed you will see the miracle. The bright chink is traversed longitudinally by dark lines! And the chink itself has become invisible. You no longer see the sharp edges of the cards—you see only a system of light and dark streaks. Where the light really ought to be, just in the middle of the chink, it is extinguished. And where no light ought to be, on either side of the chink, in the shadow of the card, you will see light.—Now I take a needle and prick a small hole in the lamp-shade; here we have a punctiform source of light. A second hole is pricked in a card, and if I bring this hole up to the punctiform source of light it seems to grow larger, and blurred at the edges, and may even appear to be surrounded with a coloured fringe, or black rings. Again, the effect of the waves!



Think once more of the wide wave-front hastening towards a breakwater (p. 137). If there is only a narrow gap, of the same order of magnitude as a wave-length, the waves spread out in all directions after passing through the gap, and the "image" of the gap appears enlarged and blurred; and this effect is more pronounced in proportion as the gap is narrower. It is just as though one had cast a stone into the water at the site of the gap, thus generating the familiar circular waves: The narrow gap has itself become a "secondary wave-centre." You can confirm the experiment at any time in a basin of water.



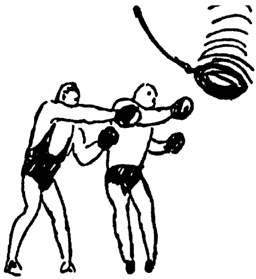
So we see, light is not as innocent as we thought. The

simple notion of a "ray of light" proves insufficient as soon as our apparatus approaches the region of the wave-lengths—that is, as soon as the slit or hole is small enough. It will soon be three hundred years since the Jesuit Father Grimaldi first discovered this phenomenon of *diffraction.* He found that in certain circumstances light appeared in the middle of a shadow, and that light plus light can be equivalent to darkness. Grimaldi could not understand this. He did not believe in the wave-motion of light—nor did anyone in his day; for at this period a single mighty name was supreme—the name of Newton. Irresistibly, his genius compelled his fellow-scientists to think as he did. They all thought as Newton thought—they had to, they couldn't do otherwise. A Titan forced his science upon the world. Grimaldi's diffraction experiments furnished the clearest imaginable evidence against Newton's corpuscular theory—for Huygens, who desperately but vainly fought an unequal battle with the demigod. Grimaldi's experiment was forgotten. A hundred and fifty years were to pass before the world freed itself from the spell in which Newton's great spirit, even in death, held it bound. Fresnel in France and Thomas Young in England helped the wave-theory to conquer. Fresnel, young and careless of dogma, devised the first interference-experiment.

Could the trains of bullets from two machine-guns—to take an image consistent with Newton's corpuscular theory—fired in the same direction, cancel each other out? No, they could only reinforce each other! But two trains of waves, running together and side by side, can disturb each other—we say, they cause interference—if they are not perfectly in step. One wave will lift a boat just as a second wave is trying to swing it downwards. As a result, the boat does nothing at all; it remains at rest.

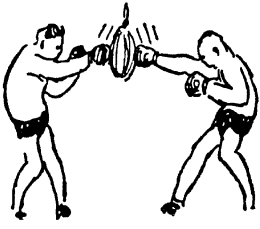
A boxer pummels a punching-ball. With a constant rhythm, it sways to and fro, always hit at the proper time by the bruiser—just as a particle of ether vibrates if it is constantly pushed in the same tempo by an electromagnetic wave. A second boxer comes up, and now all depends on his temperament. He, too, we will suppose, if he were left to himself, would punch the ball in the same tempo—to and fro, to and fro. And if he is

an accommodating fellow, he will cut in at the right moment —and under the twofold blows the ball will sway twice as far, always in the same tempo, to and fro. Two light-waves of the same length will give twice as much light. A matter of course, you think? But if the second boxer's breakfast has disagreed with him, or if he has some grudge against his partner —what then? Then he will cut in at the wrong moment; he will punch as fiercely and rapidly as the other—but in the opposite direction. Like machines the two men, with distorted faces, slog away at the ball—and the tortured



thing comes to a standstill, quivering and helpless, between the two! The ball will not move. An ether-particle pushed and tugged by two similar light-waves, which are oscillating out of tempo, so that the peak of one corresponds with the trough of another, will similarly be unable to move. Two light-waves can cancel each other out. Light + Light = Darkness. So Young and Fresnel discovered. And with that the decision was given in Huygens' favour, and against Newton.—They discovered still more. They found that light is a *transversal* wave-motion.

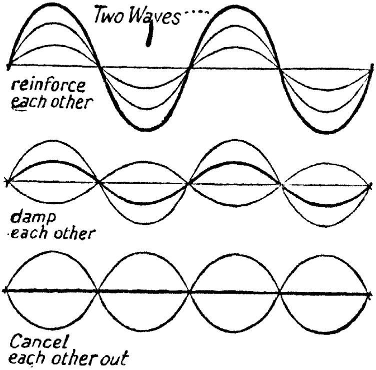
There are two possible kinds of wave-motion: *Transversal*, like water-waves. The water sways up and down—and the wave runs across the surface at right angles to this motion. And *longitudinal*, when the wave runs *in* the direction of the wave-motion. Such a wave is the sound-wave; the particles of air sway to and fro in the direction of the sound. Compression of the air and rarefaction alternate.—What



sort of wave could the light-wave be? One would have thought —longitudinal. Only in substantial, elastic bodies could transversal waves arise. In gases there are only longitudinal waves (because there is no perceptible attraction between the atoms,

but only repulsion, when they approach one another too closely). And is not the ether a gas? Isn't it infinitely subtle and fluid, and distributed throughout all space? It seems so, doesn't it? But Fresnel had to decide in favour of transversal waves—much against his will; for he clearly foresaw the difficulties.

Did you know, by the way, that the boxer at his punching-ball is "linearly polarized?" I am not joking—it is perfectly true. He strikes always in the same tempo—and always in one direcion. The ball oscillates always in one plane—always



parallel (say) to the wall, which runs north and south. This and nothing else is a linearly polarized boxer. (Polarized = directed.) And now Fresnel tries his second experiment. Once more, with a grim expression, the second boxer enters; only this time he does not stand in front of his opponent, but on one side; he is going to box east and west. The second boxer, too, is linearly polarized—yes, but in another direction: at right angles to the first. We can guess what happens. The ball receives blows aimed in two directions—and it gives way, in both directions, as far as it can. As for how it will move—that is soon said. It depends on the tempo, and on the moment when the first blow is struck. If both blows are struck simultaneously, the ball will dodge aside obliquely. (Compare the theatre-inn-cinema example on p. 80.) It oscillates in a straight line, but obliquely between the two boxers (linearly polarized).

But if the second man is obliging he will always strike in the intervals between the other's blows—and then the ball will fly round in a circle. It will describe a circular orbit (circular polarization). And if the second boxer's blows are not struck in the middle of the interval between the other man's punches, the ball will oscillate neither in a circle nor in a straight line, but in something between the two—an ellipse (elliptically polarized). But never, be it noted, never in these circumstances will the ball—or the particle of ether—come to rest. Two light-rays that are polarized at right angles to each other can never cancel each other out; they do not *interfere*.

This was discovered by Fresnel, as the outcome of his experiment. In the case of a longitudinal oscillation such behaviour would be impossible—so he had to come to the unwelcome conclusion that light is a transversal oscillation—that is, that the luminiferous ether is a solid substance! A solid substance which is infinitely subtle and penetrates all the matter in the Universe! No wonder that Fresnel and Young did not feel particularly comfortable about this consequence of their theory! And when one learns what mysterious mechanisms, with screws, and cog-wheels, and gyrating rings, or masses of frothy consistency, the physicists devised in order to construct a working model of the ether, one is quite intimidated by this witches' sabbath, and almost inclined to doubt whether there is any sense in physics!

Thank goodness, we needn't perplex our brains with Young's misgivings—we have known for a long time that light is not an elastic, but an electric oscillation. Why, then, should we puzzle our wits about the ether? We shall soon enough find other things to puzzle us.

It still remains to be explained why no one, before Fresnel's time, thought the interference of light a logical and reasonable phenomenon. The explanation is simple enough—no one had ever thought of fixing the position of the boxers. Ordinary light, of course, is always linearly polarized; the electrical vector oscillates in one direction, one plane. But a proper boxer doesn't always box north and south; he dances round the ball, changing his position from time to time, with little elastic steps; his movements are unpremeditated and irregular.

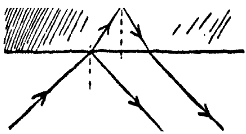
A light-ray does the same; it changes the direction of its polarization, in an arbitrary and irregular fashion—perhaps a thousand, perhaps a million times a second. If we remember that the frequencies of visible light lie between 400 and 750 billion oscillations per second—corresponding to wave-lengths of $0{\cdot}7\,\mu$ to $0{\cdot}4\,\mu$—we shall see that even if the direction of polarization changes a million times a second there will still be millions and milliards of oscillations in each direction (see *Waves*, p. 111; and remember, in connection with all these calculations, that Frequency × Wave-length = Velocity of light, 300,000 kilometres or 186,000 miles per second).

It is obvious that with a boxer dancing around in such a disorderly manner it is impossible to devise any satisfactory interference-experiments; unless indeed his opponent hops around in exactly the same manner, always in the same tempo, as though he were part and parcel of him. And as a rule, of course, boxers actually do this—they are and remain linearly polarized, both punching in the same plane, always opposing each other.

It is plain that no interference experiments can be devised with two ordinary rays of light; unless indeed the planes of polarization of the two rays are fixed—or at least, relatively fixed, as in the case of the two pugilists. This is exactly what happens in the case of a very narrow slit or a small orifice. On both sides of the slit Huygens' spherical waves are formed; but they are caused—and this is the important point—by one and the same ray of light, and both sets of waves are polarized in the same direction: this being so, they are able to interfere, and their interaction gives rise to the light and dark lines which fill the slit.

Fresnel was the first to grasp the significance of polarization. In his first attempt to obtain "artificial interference," the famous mirror experiment, he applied the same principle. He divided a ray of light into two halves, reflected it, and allowed the two halves—which were both in the same state of polarization—to interfere. To this day all interference-experiments are based on this device, by which—let me say it again—the planes of polarization are relatively fixed, so that the two boxers are constantly opposed to each other.

At night, in the tram or motor-bus, we may often note the superimposition of two worlds: the real, brightly lit world outside the window, and a rather pale, sketchy world—the world of our own reflection—in the window-pane. Window-glass is not a perfect reflector; only 4 per cent of the light falling vertically upon it is reflected; 96 per cent goes through. Of course, the more acute the angle at which the light strikes the plate, the less goes through it, and the greater the proportion of the light that is reflected. But a light-ray is always divided when it strikes a glass plate; part of it is reflected, and part of it enters the plate and is deflected in accordance with the laws of refraction. A fraction of the entering light is reflected from the farther wall of the pane; so actually two reflected images are always formed, which you can see in a bad mirror—separated only by a slight mutual displacement. In a good mirror the principal image, which is reflected from the silvered surface, is so much the brighter that it "shouts down" the other. But the two mirrored images can interfere with each other, especially when the glass is thin enough. Whether they reinforce or cancel each other depends on the thickness of the glass, and also the wave-length. With a certain thickness of glass the blue is cancelled, and red remains; with another thickness blue is the fortunate survivor, and the red is extinguished. The thin glass seems to be coloured—with the "colours of thin laminations." Hitherto the whole question of interference may have seemed rather dry and theoretical, but it is actual enough. The thin film of oil on the rain-wet asphalt, the tense, reflecting skin of the soap-bubble owe their brilliant display of colour to interference. And if I look at a lamp with half-closed eyes, and take pleasure in the starry rays of light which are then visible, here again I am observing an interference-phenomenon, caused by the diffraction of the light passing between my eyelashes!



A gramophone record is usually said to be black. We shall contest this assertion, and prove our case. The disk is covered

with numerous grooves, which are very close together. If you hold the disk with its edge to the light, and look across its surface at a very sharp angle, you will see the black plate light up with the most brilliant rainbow colours. Q.E.D.

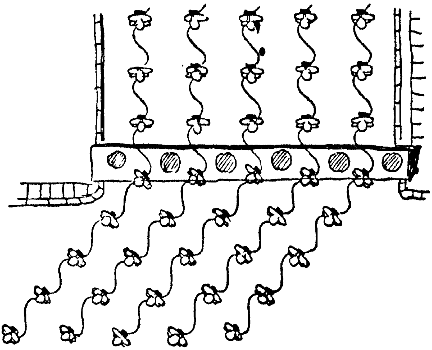
The physicist, if asked to explain the reason of this chromatic splendour, will murmur something to this effect: "Interference —the disk is a grating," and go his way. But what is a "grating," in the terminology of physics?

The Diffraction Grating

Here is an old city gate with five passage-ways. And here from the citadel comes a company of soldiers, five men to every rank, and when they come to the gate each man passes through a separate opening. On the other side of the gate, of course, their formation remains the same; the marching ranks emerge as they entered the passage-ways, in perfect order. But it seems that for some reason they must have been given the order to march, after passing through the gate, not straight ahead, but at an angle—say at a half-right angle, towards the War Memorial by the railway-station. The first rank emerges from the gate; each of the five men appears at the same moment; each makes a smart half-right wheel, and the five march on in step. But what do they look like now? This is dreadful! Where is the perfectly aligned front rank of the marching column? Counting from the left, every man is lagging behind the man on his right! The original order of march has been destroyed —but it may happen, by chance, that an order of march is still preserved. Not indeed at the head of the column—there the right file-leader has the start of them all. But it may very well happen that after the men have wheeled the right-hand man of Rank 5 is marching shoulder to shoulder with No. 2 of Rank 4, who, of course, will be lagging a little way behind his own right-hand man. On his left, exactly level with him, is No. 3 of Rank 3; then comes No. 4 of Rank 2, and the new rank ends in the left-hand file-leader of Rank 1. Here, to be sure, the old order has changed! But one uniform looks like another, and an unsophisticated passer-by, suddenly coming upon the column by the War Memorial, might take pleasure

in the spectacle of the perfectly dressed ranks, and imagine that all was as it should be. You see—there are certain given directions in which this phenomenon can make its appearance. Certain directions which enable the whole company to continue their march in regular formation—though not in the original order.

But you will see, also, that these fortunate directions are exceptional cases. As a general thing the order of march is destroyed. And you will see, too, that the "orderly direction"

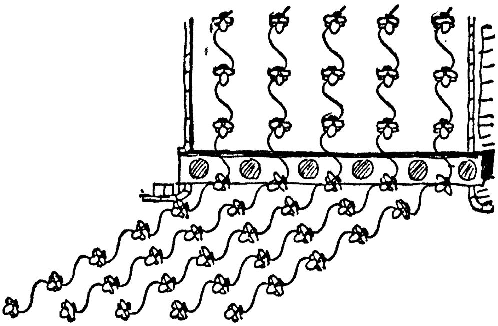


depends upon the distance between two marching ranks. The closer the ranks, the smaller the angle. The analogy is obvious. A pencil of light falls on a series of openings. After passing through the openings it spreads out in all directions, in accordance with the laws of diffraction. And there are certain directions —but only a few—in which the light can travel on in perfect order. In most of the other directions no order is preserved. Order is preserved if throughout the whole pencil of light every ray has the same "wave-phase"—that is, if all the peaks come together, and all the troughs, and all the zeros; but not if a peak has a trough for its neighbour, for then they cancel each other out by interference. After passing through a row of openings light can continue to shine only in a few definite directions. In all intervening directions it is extinguished by interference. The favoured direction depends on the size of the intervals—that is, on the wave-lengths. Short waves make

a more acute angle. Light is dissected into its component colours—as by a prism!

Such a grating is known as a "diffraction-grating." These gratings have been of the utmost service to the science of spectroscopy, thanks to their chromatic sensitiveness. But we do not make use of only five slits, like the openings in the city gate, but of thousands and tens of thousands—the more, the better.

The manufacture of such a grating is a problem in itself.



The best gratings were made by Rowland, scratched on speculum-metal with a diamond-point. Rowland constructed three dividing-machines; one is in London, one in Australia, one in Baltimore. The essential feature of such a machine is an absolutely perfect screw; its thread must be cut with faultless accuracy and uniformity, without the least "backlash." Rowland was able to cut 20,000 lines to the inch—800 to the millimetre—over a length of 14 centimetres. Each line is therefore less than 1 μ in width—for there are, of course, intervals between the lines—so that its width is of the same order of magnitude as a wave-length.[1] A large diffraction-grating is a precious thing, a scientific rarity. It is treated with

[1] Since Rowland made his gratings, electrotypic and celluloid casts of "master" gratings have been made and employed with success; and even photographic contact copies have been found serviceable.—TR.

the utmost care, and housed in a special underground room, where a pedestal of concrete blocks protects it from vibration, and it is also carefully guarded against changes of temperature and atmospheric variations. The very word "grating-room" is enough to make a spectroscopist walk on tiptoe.

Many butterflies and birds, of course, have excelled the work of Rowland's dividing-machine. Their feathers and wings are covered with delicate, regular ridges—tiny diffraction-gratings. When light falls upon them a shimmering, changing play of colours is visible—interference-colours.

In the year 1912 a wonderful and unforeseen application was made of the principle of the diffraction-grating. It was Professor von Laue who made the great discovery.

The physicists were familiar with the Röntgen-rays, and they strongly suspected that they were a wave-radiation—but it was not possible to measure their wave-length. The most ingenious experiments and apparatus were employed in vain; optical gratings, with which visible light can be measured with an error of only $\frac{1}{10,000}$ per cent, proved to be useless. The Röntgen-rays simply shot right through the grating, unhindered; not a trace of diffraction was observable. Rowland had scratched as many as 20,000 furrows to the inch on speculum-metal; the microscope could no longer reveal the structure of the grating. But it was still a monstrous and clumsy instrument for the infinitesimal Röntgen-rays—as monstrous as the openings in the city gate would be compared with the ripples in a wash-hand basin. The case was hopeless. Apparently it would never be possible to rule sufficiently fine gratings.—And then someone discovered that there already were such gratings in existence—and had been since the beginning of the world.

Max von Laue hit upon the wonderful idea of employing the grating of the crystal. In astonishing regularity, far more exactly than in the best of our instruments, atom lies beside atom in a crystal of rock-salt. We know the "grating constant" of the crystal—the distance between two atoms. We know that this is 0·24 of a millionth of a millimetre. And for the first time Laue sent a Röntgen-ray through a crystal.

Every atom bends the oncoming wave a little, and throws it

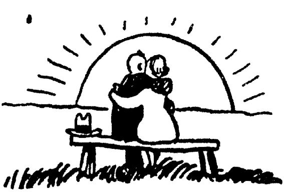
out of its course. Just as in the case of the optical grating, there are certain favoured directions in which all individual waves reinforce one another, producing a maximum brightness. Just as in the case of the optical grating, the waves cancel one another out in the intervals. Just as in a pillared hall with regularly placed pillars, or in a wood of geometrically planted trees, we can obtain a free view only in certain directions, so the rock-salt crystal allows the Röntgen-rays to pass only in certain directions; and a photographic plate placed behind the crystal shows a system of dispersed points, arranged at regular intervals. This image of interference-points (the Laue diagram) is a symbol—more, an exact picture—of the framework of the crystal. Those who have learned how to look at it—that is, those who have mastered the mathematics of the theory of the diffraction grating—see in these insignificant black specks a picture of the atoms in rock-salt.

This idea was fertile of results—it became, in the course of a few years, in the hands of Debye and Scherrer, and above all the two Braggs (father and son), a truly magical instrument. It revealed the last secrets, in exact figures, of the intricate microstructure, the crystalline nature of matter. By means of Laue diagrams we can determine as exactly as by a chemical analysis the nature of a mixture. Today the "internal examination" of a material by Röntgen irradiation has already found a place in the equipment of the technician; in many factories important castings and forgings are irradiated by Röntgen-rays. Marine boilers, large tubes, and so forth, cannot, of course, very well be taken into the testing-room; but nowadays even they can be examined. There are today mobile testing-trucks which come to the material where the material cannot come to them. The truck contains the necessary equipment—a camera and a portable Röntgen tube, which can readily be passed into the interior of the boiler. The current is switched on for a few seconds, the plate is exposed and developed, and hidden flaws, strains, and distortions in the molecular structure are immediately revealed. Today we are no longer justified in regarding the theory of interference as irrelevant or useless.

The Velocity of Light

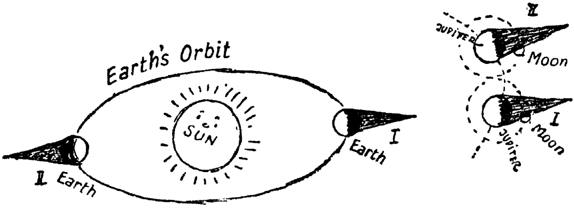
Years ago, when I began to study physics, I came across a drawing which pleased me enormously: a professor was observing the sunrise, watch in hand, and saying, with an air of satisfaction: "Good—the sunrise is fairly punctual!"

But does the Sun rise punctually? When we see it appear on the horizon it was really there 8½ minutes earlier; when it sinks in the West we see it for 8½ minutes after it has really set! This sounds a little improbable, I know. Nevertheless, it is true; for the light of the Sun takes 8½ minutes to reach the Earth.



As you see, light does not travel slowly. The ancients even believed that it propagated itself instantaneously. A flash of lightning—they said—lights the whole landscape simultaneously; and therefore, they concluded, the speed of light must be infinitely great. Galileo, who doubted many things, doubted this also. He made an experiment: he placed two men with dark lanterns as far apart as he could, and gave them instructions to the effect that the first was to close his lantern, and the second, when he saw the light go out, was to follow his example instantaneously. But the result of the experiment was negative—both appeared to extinguish the light simultaneously. The margin of human error was too wide to permit of an exact result. Galileo, quite correctly, drew only one conclusion—that the velocity of light is very great; for example, greater than that of sound. Both the theories of light which were then evolved (those of Huygens and Newton) required that the velocity of light should be infinite. And in 1675 Olaf Römer hit on the happy idea—or rather, the idea was forced upon him by Nature—of repeating Galileo's experiment on a very much greater scale—namely, in space. Jupiter was his lantern-holder; one of Jupiter's moons was his source of light; and when this moon entered the shadow of Jupiter, its light

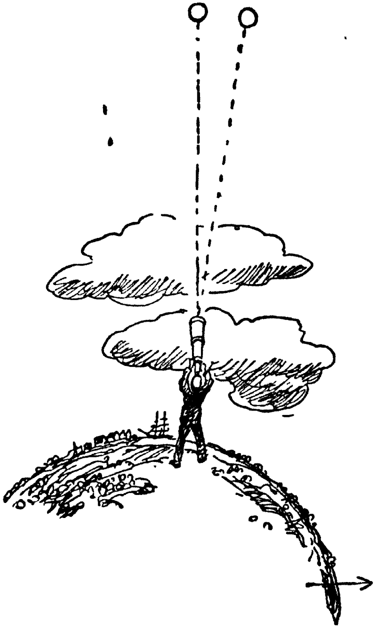
was extinguished. The eclipse of the moon was a light-signal. Olaf Römer had no ulterior motives. He had simply calculated the eclipses, and was testing Jupiter for punctuality. In the summer all went well; but six months later, in winter, he was dismayed to discover that Jupiter was slow! The moon entered his shadow no less than fifteen minutes too late! Were the calculations wrong? Once more the tables were scrutinized. In the meantime summer returned—and as though nothing had happened, Jupiter behaved exactly in accordance with Römer's calculations; it was a pleasure to see how exactly the light-signal was given, punctual to the very second. And now Römer discovered his mistake. Between summer and winter there was not only the difference of six months—there



was also the difference of the Earth's orbit! The first measurements were made when Jupiter was nearer; but six months later the Earth and Jupiter were diametrically opposite each other. The distance between them had been increased by 300,000,000 kilometres—186,000,000 miles! The retardation was due to the greater distance travelled by the light—and a simple calculation gave a velocity of about 300,000 kilometres per second. So Römer explained his observation; but his contemporaries would not believe him.

But fifty years later this chapter of astronomy was reopened —by a puff of wind. The astronomer Bradley was crossing the Thames by ferry. A puff of wind, which blew his hat off his head, startled him out of his meditations—and although his hat was lost, he began to shout for joy: for at this moment he suddenly became aware of the ferry-boat's flag: it was not blowing straight astern, as it did in calm weather, nor yet directly abeam, in the direction of the wind—it had compro-

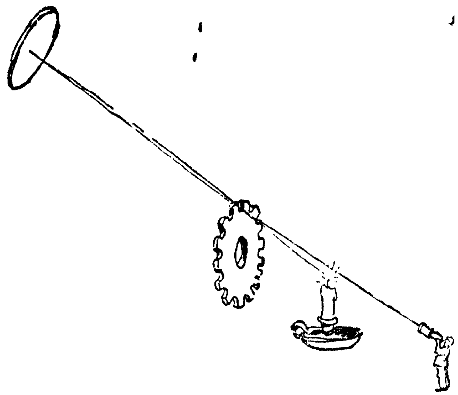
mised on the mean line between the direction in which the boat was moving and the direction of the wind. We all know what is meant by the resultant of two forces as given by the parallelogram of forces. But to Bradley it was something new, and for him it meant the solution of the problem over which he had been pondering: the aberration which he had observed in the fixed stars. It is obvious that if light takes a certain time to reach the eye through the telescope, and if during this time the telescope is carried onwards by the Earth, the light-ray will be left a little behind, and the image of the star will appear, not in the middle of the field, but a little to one side. And since the Earth and the telescope describe a whole circle in the course of a year, then in the same time the fixed star under observation will likewise describe a little circle—a faithful miniature of the Earth's orbit. Just as the hunter who is shooting at a running quarry has to aim a little in advance of it, so Bradley had to point his telescope a little in advance of the star. The velocity of the Earth is known; so the velocity of light can be calculated. It proved to be 300,000 kilometres per second—Römer's value—and now the doubters were silenced.



Fizeau was the first to conceive the audacious idea of determining the velocity of light on the Earth.

He applied the principle of the turnstile. A ray of light

was sent through a revolving door—in Fizeau's experiment, through the gap between two teeth of a motionless cog-wheel. It fell upon a little mirror, and was returned through the same gap, into a small telescope, where it appeared as a point of light. This mirror was fixed at a distance of ten, twenty, even twenty-five kilometres from the source of light; it was placed at the focus of a second telescope. To direct it so exactly that the ray was accurately returned into the same gap was a masterly achievement; for to adjust a light-pointer more than



six miles in length to a millimetre is no easy matter. And now Fizeau's real experiment begins. The point of light shines brightly in the telescope, and he gives the order to turn the toothed wheel. The gear-wheels run faster and faster; two, four, ten revolutions a second—and still all is bright. The light-ray completes its trip across country in a fraction of a second, and still finds a gap on its return. "Faster," says Fizeau, his eye pressed against the eyepiece. Eleven, twelve—and then, at 13·2 revolutions, the expected miracle occurs—the light is suddenly extinguished. Swiftly as the light flashes across the countryside, the toothed wheel is too quick for it, and on its return it finds the turnstile closed against it. A tooth bars the way.—The experiment was continued. The wheel revolved more swiftly still—and again, at 26·4 revolu-

tions, the point of light suddenly reappeared; the light was now passing out through one gap and returning through the next.—This was the celebrated spot of light whose disappearance brought enlightenment; with a toothed wheel and a mirror Fizeau had measured, on the Earth, the velocity of velocities, the greatest velocity possible in our Universe.

Together with Foucault, he afterwards devised a second experiment: the method of the rotating mirror.

The light falls on a mirror, is reflected a little way, and falls on a second mirror, which sends it back to the first, and then into a telescope. The first mirror is now rapidly rotated, so that the returning ray finds it slightly displaced, and on reflection it does not follow exactly the same path as it would if the mirror were motionless. The quicker the rotation, the greater the deviation. Foucault and Fizeau reduced the path of the light to a few metres; they measured the velocity of light in the laboratory.

This experiment was likened to a "steeplechase after the velocity of light." For Fizeau and Foucault, who had first worked together, separated because they could not agree as to whether the mirror should be rotated by a turbine or a train of clockwork. Each went to work feverishly in his own fashion. But Fizeau had bad luck; ridiculous obstacles, such as a defective zinc tube, delayed his experiment, and so Foucault was able to make the decisive communication to the Académie Française a few days in advance of him.

The rotating mirror method has been brought to the highest perfection in America—by Michelson, after protracted experiment. A stretch of 65 kilometres—between two mountain-tops —was measured by an army of Government surveyors, to within two inches. The mirror, and the compressed-air motor for driving it, were constructed with the greatest ingenuity. The light was also sent through long tubes full of water or carbon disulphide, and its velocity in them was measured. These were experiments on a great scale, such as would be possible only in America, and to an unrivalled experimenter like Michelson. And thanks to these experiments, Michelson has been able to determine the velocity of light to within a few kilometres. It is 299,796 km./sec.

And here are his own words:

"The determination of the velocity of light is one of the most fascinating problems of physics—by reason of its almost inconceivable magnitude, together with the tremendous exactitude with which it can be measured."

If you have no objection, we will do something of which Mr. Michelson would not approve. We won't trouble our heads about his result; in our calculations we will always take the round number 300,000 km./sec.—conscious, of course, that we are really doing wrong.

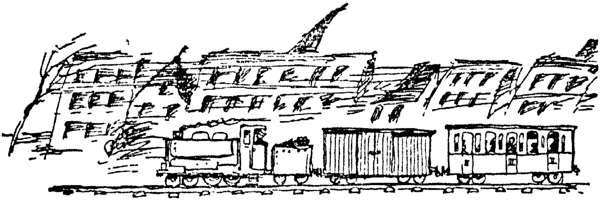
PART FOUR

THE THEORY OF RELATIVITY

THE THEORY OF RELATIVITY

Motion and Velocity

ON the speed-track the racing cars flash by—ten, twelve in a flock; long, low, fine-drawn machines, whose only joy and purpose is the race. They come, and they are gone—almost before the eye has seized them. And overhead, in the cloudless sky, an aeroplane is gliding slowly and quietly upon its course. —Slowly? But, good heavens, it is flying twice as fast as the racing cars! Anyone who has ever flown in an aeroplane knows



how the machine seems to stand still above the map-like landscape outspread beneath it, and how, on descending, it suddenly tears across the aerodrome! Then, when it is almost too late, we realize, in a flash, the speed of its flight. Everybody has at some time or other found himself sitting in a railway-train, motionless in a station, and has asked himself, when another train has pulled up beside his: "Hullo, are we off already?" But it was really the other train that was slowly pulling up.

In a word—we have no sense of *absolute* velocity. We can perceive motion only if there is a stationary environment: telegraph-poles, or a road-surface flashing past us. This is the bare truth: we have perception only of *motion in respect of something*. And mechanics, and theoretical physics, are in the same case; they too have no perception of absolute motion. It matters nothing to the laws of mechanics whether an aeroplane is flying through the stationary air, or whether it remains at

rest and is blown upon by a gale of wind—such as the research-worker investigating stream-lines may set up in a wind-tunnel. The laws of mechanics give the same result in either case. The fundamental Newtonian equation, the very scaffolding of physics, knows nothing of absolute velocities; it regards only relative motions. And this is called the *relativity principle of mechanics.*

Absolute velocity—that is easily said! So easily, indeed, as to be suspect. But what does it mean? Absolute velocity? Velocity in space, of course; in universal space; and at the very thought our minds are haunted by a vague notion of a dark, empty Universe, through which our Earth is speeding. Some, perhaps, will think of the Sun, for we are told that it is tearing through the Milky Way at the rate of twelve miles per second. But let us make no mistake—even this is a motion relative to something—relative to the starry heavens. We measure the position of the fixed stars, and their apparent displacement, and we determine, from the light which they send us, the apparent velocities of the stars; and all these observations may be most simply summed up in the statement: The Sun is moving along a path within the galactic system at the rate of twelve miles per second. But this is only relative motion! And if we are honest we shall have to admit that any question as to the "absolute velocity" of this or that is meaningless. How can we even think about motion in nothingness? If there is nothing but the moving body, by what shall we measure its movement? I cannot see that the question can have any meaning. Perhaps I am physically biassed. I admit, frankly, that I too have a lively and unfounded conception of space, of Newton's "absolute space." A mere "intuition-form," says Kant. But the truth of the matter is that we simply can't help thinking of ourselves as "objects in space." Objects "outside space," "not in space"—we can write down such phrases, and we can even think about them, but we can't really *think* them, Space is the empty nothing in which something—the stars, matter—is embedded.

But can motion relative to nothing be measured? Here mechanics fails us, and so does thought, if we think honestly and logically. We must conclude that the absolute space of

Newton and Kant is not physically conceivable. Yet physics, in a very surprising manner, comes to the assistance of this ingenuous notion.

Caring nothing for the philosophical consideration as to whether such a thing is thinkable, light goes speeding through empty space. What is more, in this empty space it sets up a wave-motion in an electromagnetic field. Like Archimedes, we joyfully cry "Eureka!" The electric field is undoubtedly a physical reality—and thanks to this reality empty space becomes suddenly palpable; from a spectral nothingness it has been promoted to a measurable something with definite physical characteristics. To be sure, the hard-boiled philosopher is still free to say to us: "So what you were calling 'empty space' a little while back isn't empty at all? It contains electric fields? Then please remove these fields before you speak of empty space!"—The objection can hardly be refuted—unless by the facts. The absolute, empty space of this hypercritical philosopher, even if it were thinkable—which is, of course, doubtful—has no existence in Nature, and is therefore, physically speaking, quite uninteresting and unreal. Our space, the space of the Universe, can exist only in conjunction with the possibility of the occurrence of electric fields. It is not possible to separate the two, and perhaps we had better put it like this: Space, and the vehicle of the light-field, the ether, are one and the same. Here we have endowed space with a new property; but it is a physically conceivable property, and we now find that it is possible to form a physical conception of space itself.

At the rate of eighteen miles per second the Earth spins in its orbit round the Sun. It flies through space, through the ether; the ether—if we think of it as being at rest—flows past it, unhindered, immaterial. So a gale of ether is constantly blowing through our laboratories. It does not matter what the true motion of the Sun relative to the motionless ether may be; the Earth, in its orbit, is now moving in the same direction, and six months later in the opposite direction. Consequently the ether wind ought to be perceptible in optical or electrical experiments. We must surely be able to measure the motion of the Earth relative to the ether—the absolute motion which we had almost given up as unthinkable?

The Michelson Experiment

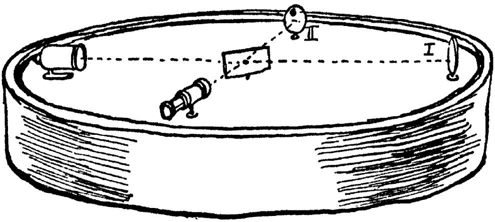
Maxwell was the first to see a glimmer of hope in this direction. His ideas were followed up by that ingenious experimenter, Michelson. Experimentally, he investigated "the motion of the Earth relative to the luminiferous ether." There can hardly have been another physical experiment to achieve such celebrity as the "Michelson experiment"—and probably none has been more hotly debated. This may perhaps be explained by the fact that the experiment had an intensely dramatic quality: it put a brief, unmistakable question to Nature, which could be answered only by "Yes," or "No"; an evasive answer was impossible. As a prosecutor builds up the whole fabric of his case on a single decisive point, and suddenly flings out this fateful question, so Michelson had planned his experiment. The defendant ether did not make things easy for him. It seems to have obliterated its traces with malice aforethought.

If I carry out one experiment "with the ether stream," and another "against the ether stream," it appears, from the calculation of the celebrated Dutch investigator, Hendrik Antoon Lorentz, that the two results will differ to the extent of 0·00001 per cent. The case would seem to be hopeless; for who could measure such differences? The Earth had to wait for Michelson, with his amazing experimental technique, before it could hope to obtain information as to its state of motion.

I will tell you a little story with which you can annoy your friends. A steamer sails from Hamburg to New York (3,600 miles) and back, at the speed of six miles per hour. A second steamer sails with a speed of three miles per hour, but returns, without ballast, with a speed of nine miles. Which gets back to Hamburg the sooner? Please don't say: they both get back at the same time. The first requires twice 600=1,200 hours for the double voyage; the second makes the outward voyage in 1,200 hours, and returns in 400 hours: in all, 1,600 hours. It was unable to make up for the loss of time on the outward voyage.

Get into a river rowing-boat, and row a hundred yards

across the stream and back again. And get a second boat to row, at the same rate, a hundred yards upstream, and then the same distance downstream. Although the first boat will have to keep its bows upstream all the way, in order to avoid being carried down by the current, it will get back sooner than the other, because here again the second boat cannot make up for the loss of time on the slow passage upstream. Well, this is exactly the principle of the Michelson experiment. Michelson allowed a ray of light to fall on a glass plate, and the ray (as we saw on p. 161) was there divided into two parts: a transmitted ray (I) and a reflected ray (II). Ray I is despatched



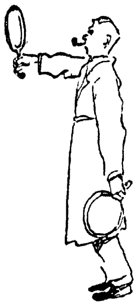
in the direction of the Earth's motion—that is, against the ether-gale that rushes through the laboratory; it falls on a mirror, and returns to the glass plate, whence it is reflected into a telescope. Ray II travels the same distance *across* the ether-wind, is reflected by a mirror, returns to the glass plate, and passing through it, enters the telescope with the other ray. Now here again Ray II ought to arrive the sooner. Michelson observed in the field of the telescope a system of light and dark interference-bands. When the whole apparatus, mirrors and all (which is known as the Michelson interferometer), is rotated through an angle of 90°, the two rays exchange their rôles, and now Ray I ought to win the race. On rotating the interferometer there ought to be a shifting of the interference-bands in the field of the telescope.

This was a masterpiece of experimental physics, and the sensitiveness of the apparatus was incredible. The 0·00001 per cent limit of Lorentz was far exceeded: the apparatus would show a difference of one thousand millionth!

By repeated reflection the path of the light was increased

to 11 metres. The whole apparatus was mounted on a great stone slab, and floated in a trough of mercury, in order to facilitate a perfectly smooth, vibration-free rotation. The exact adjustment of the mirrors and the telescope was the work of weeks and months.

Michelson looked into the telescope at the black and yellow interference-bands. The block of stone to which the apparatus was anchored rotated smoothly, without friction—and the interference-bands never shifted a hair's-breadth! The greatest experiment in the history of physics had—failed!



I must ask you to consider Michelson's experiment again "from outside"—say, from a soft, comfortable spot on the surface of the Sun. We see the Earth hurrying along her orbit at the rate of eighteen miles per second. Here there is no doubt about the matter—this is a measurable relative movement of two bodies: Earth and Sun. We see that both light-rays arrive at the same time. But at last, from our place on the Sun, we see quite plainly that the light has to run after the Earth and Mirror I, and overtake them, and then, after reflection, oppose the motion of the Earth, so that in the end it has to cover a greater distance than the ray that runs athwart the motion of the Earth. That is so, isn't it? Not a doubt about it? Well, let us take a big telescope! And now we see that the arm supporting Mirror I has moved just a little nearer to the telescope; the stone block has *contracted* in the direction of the Earth's orbit; the arm parallel with the Earth's orbit is shorter than the arm that lies at right angles to it! And this contraction, as though some malicious spirit had contrived the matter, is *exactly* sufficient to make the two rays arrive at the same time: and it was this alone that prevented Michelson from learning something about the motion of the Earth. We call this shrinking the Fitzgerald–Lorentz contraction, because Fitzgerald and Lorentz were the first to think of explaining the negative result of the Michelson experiment by this contraction of the stone block.

Poor Michelson! Was he blind? Apparently he never noticed the unfortunate misadventure of the Fitzgerald-Lorentz contraction—never realized that when he rotated the crossed arms the transverse arm slowly shrank as it swung parallel to the Earth's orbit, while the parallel arm slowly grew to its full length?

No; we ourselves are blind if we ask such a question. Our surprising observation is correct—but our unfavourable comment was over-hasty. For it goes without saying that Michelson's stone block was not, in some inconceivable manner, singled out from the flux of cosmic events and especially endowed with this supernatural power of contraction; but everything on the Earth contracts in the same way. If we look more closely we shall see that Michelson himself has shrunk in the same degree. His right arm, with which he is now pointing in the direction of the Earth's orbit, is shorter than the left, which lies across it. Is he a cripple? He would indignantly deny the imputation, and quite rightly. For all men and things on the Earth are subject to the same contraction. Of course, they will never perceive the fact; for the eye is shortened in the same degree, and thus remains in the correct relation to the retinal image. All earthly yardsticks and tape-measures, "shoes and ships and sealing-wax, cabbages and kings"—all, seen from the Sun, suffer the same contraction. Are we therefore to say that they are deformed?

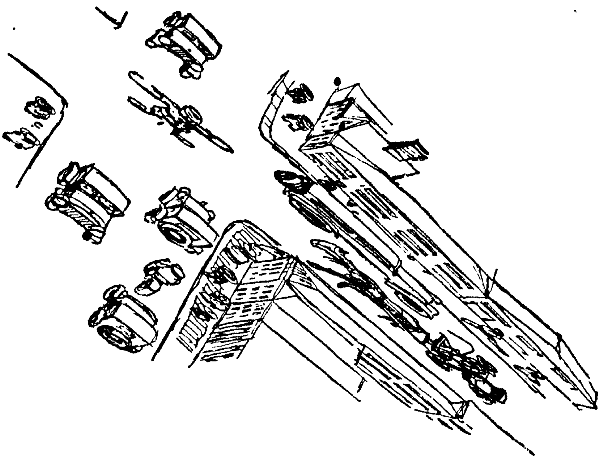
When the pound sterling fell to thirteen shillings nobody in Great Britain noticed the fall. Ten cigarettes still cost sixpence, and a Rolls-Royce two thousand pounds. Seen from outside, of course, from Germany or America, a perceptible devaluation had occurred, a "contraction." But a country whose valuta has likewise undergone devaluation notes only a very slight shifting of relative prices. It is the same with the inflation of the measuring-rod in the theory of relativity. A Martian, for whom the Earth would move more slowly than for us solar men, would note only a slight contraction. In other words: The contraction depends upon the relative velocity—the greater the velocity, the greater the contraction. At a velocity of 160,000 miles per second a yardstick would have shrunk to 18 inches. At the velocity of light it would contract to a mere point.

Hi—you're Flat!

An aviator was swooping comfortably through space. One could not call his a slow machine; for it was travelling at the rate of 259,000 kilometres per second. But for the moment his speed did not trouble him—indeed, he was not conscious of it—and now he saw the Earth in the distance rapidly approaching him. "The Earth is a spheroid," he had learnt at school. But could this be the Earth? It was a huge Easter egg, an egg standing on its pointed end, with its waist measurement strangely reduced. Now he was drawing nearer; now he could make out steamers, motor-cars, and human beings. And suddenly he began to laugh. He laughed until the tears ran down his cheeks. Shaking with irrepressible merriment, he made a sign to his passenger. "Look at those people!" And then they both leant out of the window, and shouted, still grinning all over their faces, to the waving people down below: "Hi—you're flat!"

And so they were. It seemed to the aviators as though they were looking at a world of flounders—flat, shallow-chested figures, men who went about the Earth like walking planks. But how was the world itself constructed? It was a crazy sort of place. Wide avenues ran through the city in the direction of the aeroplane's flight. Narrow lanes, only half as wide, ran across them. Flat faces, wherever you glance, in the main streets. And just look at the shop doors and windows! Flat and tall and narrow, like Gothic arches. And the omnibuses—broad and telescoped, as though they had been given a blow on the radiator. Don't they realize it?—Now, look, now you'll see something! A widely spaced company of flattened soldiers is marching through the street, taking up its whole width, twenty abreast. They want to wheel to the right, into that narrow lane? How will they do it? I don't see how. . . . But then the airmen simply gaped with astonishment—for the soldiers made a right wheel and marched straight into the narrow street. As they wheeled they had drawn together. They were still flat, but flat the other way—like long planks instead of broad ones. With sharp noses and long, swinging

arms and legs—like toy wooden soldiers, like the flat, unperspective Egyptians on the old bas-reliefs. And only now did it occur to the two airmen: this was an indiarubber world. These people were like rubber flounders. It was almost too much. Here came a short, broad omnibus; it turned the corner, drew out like a concertina, and went its way like a caterpillar. A fat, broad-chested man came towards them with short,



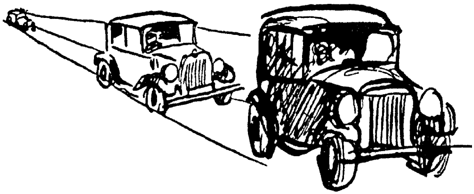
tripping steps—and went off round the corner as a narrow, long-legged shadow. A policeman was regulating the traffic; the poor fellow had two unequal arms, and when he turned round they shrank up or stretched themselves out like the horns of a snail. It was hardly credible that people could live, and perhaps be happy, in such a world! And yet they seemed happy enough—for down below a crowd of people was gathering in the great market-place—people who had heard of the arrival of the express aeroplane, and were now staring up at it. And these people were laughing uproariously, and gesticulating—and it was dreadful to see how their arms and faces were shortened and distorted as they gazed and pointed into the air! And they were shouting up at the visitors. The airmen listened, tensely, but the words were unintelligible, until at last a single

loud shout reached their ears. A flat, snub-nosed little fellow was roaring up at them: "Hi—you're flat!"

And so they were! The people in the crowded market-place saw a singular aeroplane approaching them—an aeroplane that seemed to have been telescoped by some giant hand. It was apparently reduced to half its length, and the rudder was almost touching the wings. And the men in it were—flat! They too seemed to be made of rubber; they too changed their shape, accordingly as they were looking in the direction of flight, or at an angle to it. In short, the people on the ground thought themselves normal, and the others crazy. And not only that—these two airmen, despite the speed of their flight, seemed to be afflicted with an incomprehensible lethargy and weariness. They moved very slowly, and everything they did took them twice the normal time. A gramophone record which played for 3½ minutes on the ground apparently took seven minutes to play in the aeroplane. The clock on the dashboard, which at noon had agreed with the town-hall clock, showed only 12.30 an hour later. They were not merely india-rubber men—but even their time was different! Need I say that the airmen had the same opinion of us—that for them our time passed more slowly? That our motor-buses seemed to be making fifteen miles an hour instead of thirty? It was not a cheerful encounter—and both parties sighed with relief when the hurrying aeroplane became a tiny red point on the horizon, and disappeared.[1] Phantom? Delusion? Hallucination?

[1] That an aeroplane travelling at 259,000 kilometres per second would have flown past the Earth and out of sight in a fraction of a second, and would have reached the Sun in ten minutes, need not trouble us here. We can, after all, imagine a gigantic Earth or planet millions of miles in diameter; or we can give the airmen a telescope so powerful that they could observe the Earth long after they had passed it. Of course, the pilots must bear in mind their ever-increasing distance from the Earth, and must not forget that light also has a limited velocity, and would thus take more time to travel from the gradually vanishing Earth to the aeroplane. This "travelling time of light" must be taken into account in all observations. We know, for example, that the sunlight takes 8½ minutes to reach the Earth, so that we always see the sun as it was 8½ minutes ago. These curious observations, the Lorentz contraction, and the slowing down of time, are nevertheless correct.

Neither one nor the other. The whole picture, detail by detail, is a physical, tangible reality. The Lorentz contraction is a fact. The Michelson experiment which proves it cannot be ignored. Even the slowing down of time is a fact. Two Americans have actually demonstrated it experimentally. Ought this to surprise us? But we are not surprised when a bar is expanded by the effect of heat. We are not surprised when the mercury in a thermometer rises and shrinks again—simply because the Sun shone out and disappeared. We shut one eye, and we see a motor-car, at first as small as a toy, which quickly grows larger and larger until it is a dark mass filling the whole field of vision, when it dwindles and presently disappears. No one



doubts that it is the same car which, as though by magic, grows and shrinks again. Experience, a thousand times repeated, has taught us that the car apparently grows larger because it is approaching, and that it grows smaller again in the distance. Since we have learned to see spatially, we unconsciously compare the car with a house or tree in the distance, and estimate its own distance and its actual size. But what do we mean by *apparently*?

If the velocity of light were not so great, if the effect of great velocities were easier to observe, so that we were not dependent on such delicately exact methods of research as the Michelson experiment, and if we had been accustomed from childhood to the idea of the Lorentz contraction, these would seem the most natural things imaginable. Perhaps the technique of the rocket will be sufficiently developed by the close of this century to attain the needful velocities; in space, of course, there is no prescribed maximum velocity (except the velocity of light which Nature herself has imposed as the admissible maxi-

mum). To our grandchildren all these queer consequences of velocity will be familiar, since they will have observed them for themselves; and if the novices, on their first experience of such a journey, are beside themselves with amazement, the experienced space-pilot will tactfully hide a bored smile, and will think to himself: Good Lord, these people are always the same!

The contraction is as real as anything else; it can be measured and photographed. Two photographs of the "Zeppelin"—one showing her moored at the mast, and one in flight—are not exactly the same size. To be sure, the difference is only about half a billionth of a centimetre, which is not very considerable.

In precise physical terms: A body appears largest to us when it is at rest. When not at rest it contracts in the direction of movement. But the state of relative rest is, of course, only one single state among the many possible motions. This being so, is its "resting length" actual?—Born gives an illuminating comparison: If I cut a slice from a sausage, its size will vary accordingly as I cut it straight across or askew. But is the smaller slice therefore "actual" and the other "apparent"? Is the resting length, which happens to be the greater, actual, and the other apparent? It is not the theoretical conception, but the wording of the question that is meaningless.

Let us return for a moment to Michelson and look at his experiment through his eyes: Michelson sees no trace of a contraction, but neither does he find any trace of *an absolute motion of the Earth in space.* Nature was questioned and refused to give an answer.

But no answer even is an answer. Einstein was the first who had the courage to accept this notion—in the theory of relativity, which is a *physical* theory, and can be understood only by a physical approach. Indeed, we shall see that it adheres more closely than any previous theory to clear, physical concepts, and that we do not do it justice if we forsake the plane of physical facts. It was obviously impossible, by *any* means, to demonstrate an "absolute motion," a motion in respect of the ether: To speak of absolute motion is meaningless. I can assert of any body, with the same justification or lack of justification, that it is "absolutely at rest in the ether"—simply

because this assertion is void of meaning. Only the motions of bodies relative to one another have any physical meaning. This is Einstein's first fundamental principle: the principle of *relativity*.

But if I can learn nothing of the state of motion of the interferometer in respect of the ether, then our beautiful calculations of the ether-gale which ought now to retard light, and now to accelerate it, are undermined, and must be discarded. There is only one possible assumption: The velocity of light must always be the same—no matter how the interferometer is moving. Always, in every direction, the velocity of light has the same value—not only everywhere on the Earth, but everywhere in the Universe! This being the case, the negative result of Michelson's experiment is the most natural thing in the world. If the velocity of light remains the same in all directions, the rotation of the interferometer cannot alter anything. The ether wind is simply blown away!

This was Einstein's second fundamental principle—the "law of the constancy of the velocity of light." It was physically demonstrated by Michelson with the greatest imaginable accuracy. And yet it is apparently absolute nonsense. Let us suppose that an aviator flashes an electric torch from the stern of his aeroplane, the torch being aimed in the direction of flight. We say: a flash of light is sent along the aeroplane: the aviator is travelling in the same direction; the light is travelling at the rate of 300,000 km./sec., whereas the speed of the aeroplane is "only" 200 metres per second. "For you," we say to the pilot, "the flash of light must have had a velocity of only 299999·8 km./sec. Isn't that correct?"

"How so?" replies the pilot, disconcerted. "I don't need to trouble about the speed of my aeroplane—according to Einstein. If you like I will measure the speed of the flash in respect of my aeroplane, though just now I really have other things to do."

He measures the velocity, and finds it, precisely in accordance with Einstein's principle, exactly 300,000 km./sec.

Where is the mistake? If thought and experience clash, then thought must give way. It is nonsensical to prescribe how Nature should behave—just so that we can go on thinking in

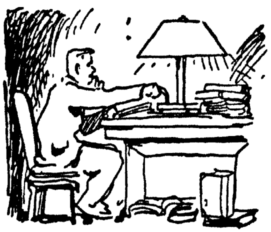
our comfortable, time-honoured way. Our ideas must adapt themselves to Nature—thought must give way to verified experience. For example, the existence of atoms cannot be doubted—and yet we can't really imagine them.

Perhaps it is better to speak of "hypothetical thinking" rather than "thinking." Logically irreproachable thinking—proceeding from correct hypotheses—will never lead to contradiction. But the hypotheses which are silently undermined must from time to time be closely examined for false or unnecessary assumptions, which may have crept in as stowaways. Einstein discovered them—it was his great achievement—in the concept of time, and especially in that of simultaneousness.

What does "simultaneous" mean?

Simultaneous?—The following conversation did really take place, although as written down here it is somewhat abbreviated and rearranged. The speakers were my friends Ewald, and Peter, and myself.

I began: "I have to ask you laymen to help me in the discussion of a difficult problem in physics. We'll assume that I am sitting at my desk in Berlin; it is growing dark; the clock is striking eight, and I switch on my reading-lamp. At the same time my fiancée in Stockholm enters her sitting-room and presses the switch of the electric light. A simple, everyday happening. Has this statement any meaning?"



"Of course," my friends replied.

"But let me ask a few questions. *In what way* are these two events in Berlin and Stockholm simultaneous?"

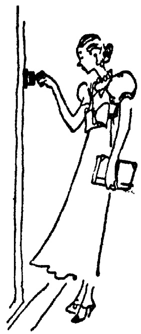
"What a question!" said Peter. "One has only to look at the clock in Stockholm; and since the clock is striking eight, there and here in Berlin, the two events are simultaneous."

"Oho!" I interrupted. "But if the clock in Stockholm is slow? My fiancée was never punctual yet. . . ."

"Then she ought to set her clock right!"

"Very well—but can you tell me *how* my fiancée in Stockholm is to set her clock by mine?"

Here my friend Ewald laughed maliciously, and said: "It would seem that you haven't heard yet of that excellent invention, the time-signal from Nauen. At exactly 1 p.m. a time-signal is radiated by the great transmitter. By that you and your fiancée in Stockholm, and thousands of people all over the world, can set their clocks—quite simultaneously."



"How wonderful!" I said. "And the man in the moon too?"

"The man in the moon too," replied Ewald. "Of course!"—And then, to my disappointment, he anticipated my next objection: "The radio waves take a second to travel the 300,000 kilometres to the Moon. So the man in the Moon, on receiving the signal, sets his clock at one hour one second. In this way, if due allowance is made for the time the signal takes to travel, the whole Universe can be provided with the normal time, and tell, by a glance at the clock, whether your fiancée in Stockholm and some queerly shaped inhabitant of one of the planets of Sirius are doing this or that simultaneously. So—what's the trouble? Of course there's such a thing as simultaneousness."

"Shall we count things as simultaneous, then," I asked, "if they're done on receiving radio or light-signals?"

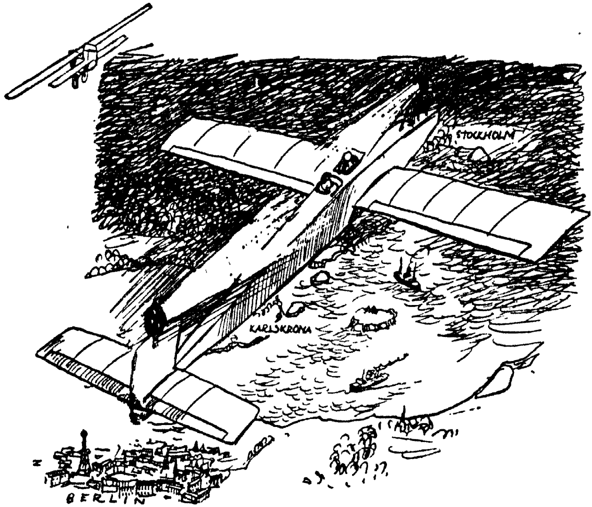
"Agreed."

"But one moment," I said: "I am going to travel by aeroplane. And lest you should raise a certain objection later, I will ask you to place at my disposal a huge aeroplane reaching from Berlin to Stockholm. The pilot sits in the middle of the fuselage, and at eight o'clock he is over Karlskrona, just halfway between Berlin and Stockholm.

"It strikes eight.—I switch on my lamp, and at the same time I light by means of a mirror, a photo-cell, or the like, the

lamp at the rear of the aeroplane, which just at this moment is exactly above my house. Both lamps light up simultaneously —there is nothing to puzzle us there. My fiancée enters her room, switches on the light, and by a similar mechanism she lights—also simultaneously—a lamp in the bows of the aeroplane. No problem there. What happens?"

"That's very simple," said Ewald. "The flashes of light



from Berlin and Stockholm reach Karlskrona together, since Karlskrona lies in the middle. An inhabitant of Karlskrona, if he should happen to be watching both Berlin and Stockholm through inclined mirrors, sees both lights flash out simultaneously. He looks at the clock, he takes the time the light would take to travel into account, and writes in his diary: Simultaneous lighting of lamps in Berlin and Stockholm."

"Very good. And the aeroplane lights?"

"They too meet in Karlskrona—just at the same time as the earth-signals!" replied Peter, who was plucking up courage.

"And now," I said, "the pilot! It strikes eight, and he is vertically over Karlskrona, and he looks at the town hall clock: eight o'clock. And at this moment both the light-signals are

made. But the pilot is flying towards the bow signal (from Stockholm!) and the stern signal is hurrying after him. And the light from the bow meets him a fraction of a second sooner than the signal from the stern. He is still sitting in his padded seat, just half-way between bow and stern; so he notes in his log-book: Karlskrona. Lighting of bow and stern lamps. Bow lamp a little sooner. The two signals were not simultaneous!"

"Sheer nonsense!" cried Peter with conviction. "Of course they are simultaneous! We have tested them by means of the radio signals, and the man in Karlskrona got the same result!"

"He's right, absolutely right!" said Ewald, supporting him. "One is accustomed to hear all sorts of things from you physicists—but I'm surprised that you don't see the mistake here. The aeroplane is *moving*; that's the sole cause of the confusion. The pilot is absolutely wrong if he thinks the two lamps aren't lit simultaneously!"

"Ewald," I said reproachfully, "what do you mean by 'move'? *You* are moving—you are rushing backwards, with the whole Earth, away from the aeroplane. The pilot has only to look out of the window to 'see' that. But are you really going to bring the dusty old concept of absolute motion out of the intellectual museum? Don't forget—physically speaking, there is no absolute motion. Don't forget the name of Michelson. According to the principle of relativity, the pilot has just as much right as you to declare that he is standing still. And as you have defined your simultaneity by light and radio signals, so he has defined his. No one can find fault with him for that. His definition is foolproof, his physics perfectly correct. If he sits between bow and stern and sees the bow lamp light up earlier than the other—then it *was* earlier. Simultaneousness is a relative conception; it depends on the relative motion of the protagonists, of their reciprocal velocity. There is a peculiar connection between simultaneousness and spatial motion. Time and space are intermingled; they are no longer independent of each other."

If my friend Peter repeats "Nonsense!" with the same conviction, there is nothing more to be done about it for the moment. One can only reflect that ancient habits of thought

cannot be thrown overboard at a moment's notice; and perhaps one might add:

One should not mix philosophy with physics; nevertheless, until the beginning of the twentieth century this was constantly done. Let me ask you a question: Do you know what time is? Of course you know. It won't be quite easy to define it, this something called "time," which has something to do with "progress" and "succession." We have, of course, a *sense* of time, a firm, unconditional conviction, beyond all doubt—an intuitive *knowledge* concerning time. But it can't easily be explained. This is the "inner" time.

Let me ask you a second question: Do you know what time it is?—You have only to glance at the clock. In this instance you are dealing with *physical* time. Ask a physicist what time is. He will reply, without a moment's hesitation: Time is that which is measured by clocks: seconds, hours, days, years. That is a plain, sober answer, with no sort of vagueness about it. We know that "inner" time and "physical" time don't always agree together. In a bad dream we can easily live through a lifetime while the seconds-hand of the alarm-clock has not even covered a full circle. But physics is concerned with clocks and not with dreams.

It is just the same with simultaneousness: this concept is for physics a notion of *a purely physical character*—it refers to happenings in this world: the flashing of two lamps, two gunshots, and the like, which can be subjected to experiment. So the concept "simultaneous" must be lifted out of the vague sphere of the normal human understanding and be physically defined—so defined that with its help natural phenomena can be consistently explained. We must get the last vestige of "inner" time out of our minds; we must retain only the notion of "physical" time. We know what we have to do: Simultaneousness, synchronism, is a concept which is elucidated by means of clocks and radio signals. It loses its universality thereby; it loses, in a sense, its metaphysical components, which our minds, with their human tendency to metaphysics, find it so hard to throw overboard. But it gains in lucidity and usefulness, and is, therefore, to be preferred. The old notion of simultaneousness broke down when faced with the Michelson

experiment; the new concept, based on the principle of relativity and the principle of the constant velocity of light, explains it.

It explains it as follows. The pilot in the aeroplane saw first the bow lamp and then the stern lamp flash out. But he knows that both lamps were lit from the ground, in Berlin and Stockholm. So the bow of the aeroplane must have flown over Stockholm rather earlier than the stern flew over Berlin; so, he says, in some astonishment, the distance from Berlin to Stockholm is now *shorter* than my aeroplane; the line Berlin–Stockholm has apparently *contracted* a little, and this can only be because it is moving, because it is gliding away beneath me. Moving bodies—and in these words the pilot expresses his surprising intuition—moving bodies shrink a little in the direction of their motion. The Lorentz contraction!

You see—the mysterious Lorentz contraction is merely a consequence of the relativity of simultaneousness. Let us say this once more: The Michelson experiment proves clearly and definitely that the velocity of light is always the same, in all directions. Michelson, therefore, could never have expected a result from it. But if we observe the Michelson experiment from the Sun—*there we have another time than his.* What appears simultaneous to us is no longer simultaneous to him. But we naturally regard *our* time as correct; we see that Michelson and the Earth are gliding past us, and we see that as a consequence of this difference of time the arm of the interferometer which is pointing in the direction of its motion contracts just as far as is necessary to produce a negative result.

I once read a story of a village parson who was induced, by the presence of some French prisoners, to begin, with his parishioners, to learn a few words of French. Of an evening the peasants and farmers sat in the pastor's study and listened to the unintelligible jargon. But suddenly one of the peasants stood up and said: "What nonsense, pastor! You can say 'chaise' ten times over—a chair is still a chair and not a 'chaise'!" Well, it's like that. French and German thought or speech are only two ways of describing the world, two formulae with the same content; but who would attempt to decide, like this

peasant, which way is the right one? The thing is obvious—the dilemma doesn't consist in the fact that there are two languages; the question is wrongly put—it is meaningless. And the question is wrongly put if we ask whether the true simultaneousness is that of the man in the aeroplane or that of the man in Karlskrona. The two men are speaking different physical languages. They are expressing one and the same event—the switching on of two lamps—in different formulae, and they cannot understand one another without a vocabulary—without the possibility of translating a French sentence into German, so to speak—the formula of the aviator into the formula of the Karkskrona man. There is such a physical vocabulary—a conversion formula. This we owe to Hendrik Antoon Lorentz, the celebrated Dutch theorist, who anticipated many of the actual results of the theory of relativity, but as a conservative thinker was not able to anticipate Einstein's absolutely new and objective mode of thought; he could not make up his mind to throw overboard the metaphysical character of simultaneousness and content himself with the bald, unadorned physical definition; attempting to defend to the very last the at least hypothetical possibility of an absolute time. But it is just this that distinguishes the theory of relativity; that proceeding from two fundamental principles, which are obvious or experimentally demonstrated, it does not shrink from generalizations—that it does not fear to proceed to the logical consequences, and does not scruple to discard superannuated prejudices.

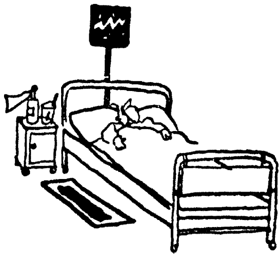
Mars and Venus are moving relatively to the Earth. Therefore another time holds good on them, and two events which are simultaneous to the Earth need not be so to Venus. But if in the near or far future men were to fly to Venus and found a colony there, who would wish to assert that their physics was erroneous? The great natural laws would have the same mathematical form for both planets.—And the principle of relativity may be described as a law of Nature.

But a thin, colourless shadow appears, a demon with a repulsive countenance, determined to annihilate the newly won definition of simultaneousness. He lays an electrical cable from a switch in Berlin to the lamp in the Stockholm house, and by

magic he so accelerates the current that when we press the switch in Berlin the lamp in Stockholm lights *at the same moment.* But then something terrible happens, and the demon has every reason to rejoice: The man in the aeroplane sees the lamp lit *first,* and *then* sees the switch pressed; for him the chain of causality runs backwards, like a reversed film. This isn't rational physics, and we make this requirement: causality must not be infringed by our definition of simultaneousness. It must not be possible that an event seen from the Earth as a cause should be seen from the aeroplane as the result of a second event, for then the principle of relativity would have to be abandoned as nonsensical. But how can we explain this nonsensical result? By the velocity of the current in the magical conductor—a velocity *greater than that of light.* The conclusion which Einstein is obliged to draw, unless he wishes to develop his theory *ad absurdum,* is obvious: There can be no such demon in the Universe. There cannot be, in the Universe, any possibility of transmitting action to a distance with a velocity greater than that of light. The velocity of light is the greatest physically possible velocity in the Universe. It signifies a limit, a limit for the motion of energy or matter.

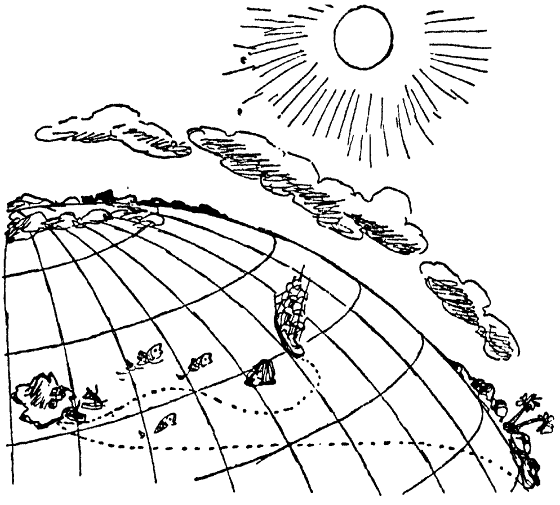
Temperature Curves

On the little blackboard at the head of the patient's bed in the hospital ward is a thin zigzag chalk-line; the temperature curve is plotted in a "system of co-ordinates." In the language of the mathematician and the physicist: here is a graphic representation of the functional relation of two variables, time and temperature. We measure the temperature every hour, mark a point on the blackboard, and connect all the points by a line,



the "temperature curve." Physics lives by such systems of co-ordinates; this is the only form in which it consents to make its findings obvious. But they are equally familiar in

ordinary life; we state the position of a ship on the ocean by giving two "co-ordinates"—geographical latitude and longitude. On a chart which is divided in this way by meridians and circles of longitude we can mark the position of the ship at any moment, and if we do this day after day we have finally marked its positions right across the ocean—we have drawn the "curve" of the ship's track. In the same way we draw on the



map the course of an aeroplane flying from London to Berlin. But it is obvious that in this case the two data given on our map are insufficient; space is three-dimensional, and the map is a plane, which has only two dimensions. If we want a real picture of the track of an aeroplane we can imitate it, above the map, by means of a thin wire; just as a switchback railway, with its loops and steep descents, is an exact three-dimensional representation of the track of the car which runs over it. But if we look at it and ask: But just *how* did the car run over the track?—then this wooden curve cannot answer us. You cannot tell from its form how quickly the car ran, or when it slowed down, where it stopped, and where it raced onwards. If you

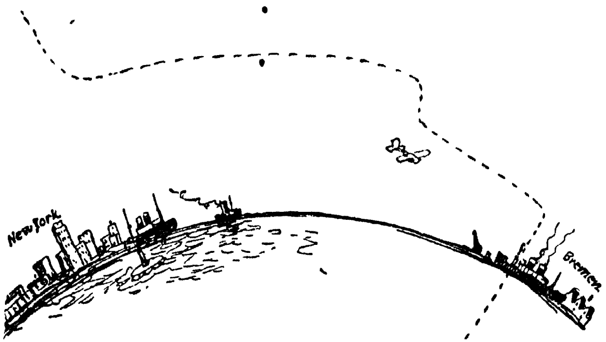
want to grasp the process completely you need a fourth dimension—*time*. Mathematically it is a simple matter to show the relation of all these four dimensions: in the equation there is room enough for four, five, and even more dimensions. Our powers of conception, of course, fail us, and we don't see how we can find a place for the fourth dimension—the time-dimension—in the spatial curve. To add to the three edges of a cube which are all at right angles to one another yet a fourth edge, which shall in turn be at right angles to all the other three, is easy enough to the mathematician, but it cannot be visibly shown.

In most cases we resort to an artifice. We sacrifice one or two spatial dimensions—and so make room for time. And thus once more we get a sort of temperature-curve, in which time has a special axis. If I know that a ship has kept strictly to the Equator during its whole voyage, it is possible to draw such a curve: The co-ordinates, for example, may be time and the distance covered. The curve thus gives a space-time representation of the voyage—although a mutilated one, for two of the spatial data have been discarded. (One of the spatial dimensions, height, can, of course, always be dispensed with in the case of ships, for ships do not, like flying-fish, lift themselves for long distances above the surface of the water. One could then represent the space-time curve in three dimensions by means of a thin wire above the map; in the case of submarines this method is useless, because they follow actual *spatial* curves, and not level paths across the ocean.) What does the curve of a steamer look like when it is lying at anchor? On the map it is a point. In our graph it is a straight line, parallel to the time-axis. The temperature-curve of a convalescent whose temperature is always 98·4° is just such a straight line.

The Track of the "Bremen"

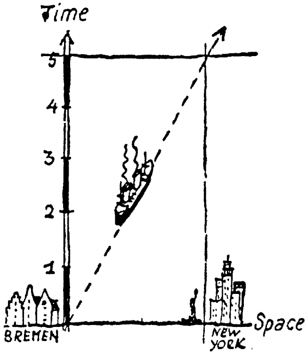
I think we may now pluck up courage to venture into Minkowski's world. Minkowski was the man who gave the theory of relativity its elegant mathematical dress. From this world of his we may gaze like the gods of Olympus on the world outspread at our feet—the human beings toiling and running

about on the flat Earth, the trains, and the hurrying steamers. We see the *Bremen* slip her moorings and leave Bremerhaven; we see her cross the ocean, and finally make fast to the pier in the Hudson River. We want the complete curve of her track—so we stretch a thin wire above her course, the height of which is to give us the values of time. What does this wire look like? First it goes straight up into the air, vertically above the Columbus quay in Bremerhaven. There from March 1st to the 2nd the *Bremen* lay moored, so for a whole day our wire



curve continues to rise. Now the ship sails—and we have to bend the wire. Gently rising, it follows the steamer on her voyage across the ocean. Suddenly, 620 miles after passing Southampton, it bends steeply upwards again; the *Bremen* must have stopped, we assume, from the look of the wire; and so she did—she took a catapult-aeroplane on board. The wire continues—flatter now, since the steamer is racing to make up for lost time; then it curves to the left when the ship altered her course, going southwards a little in order to avoid an iceberg, and before New York it once more runs steeply upwards, for there was a dense fog off the coast, and the steamer slowly groped her way forward, her siren howling, through the coastal traffic. And at last the wire bends again, shooting up into the air, vertical as a lamp-post: the *Bremen* has berthed at the pier in New York harbour. Using Minkowski's terminology, we will call this thin wire, which gives us

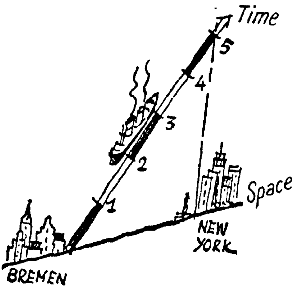
such remarkable information of all the ship's movements, a "world-line." (We may see something of the sort—though, of course, with "inverted signs"—on an absolutely windless day, in the smoke which rises vertically upwards when a steamer is motionless, and trails behind her when she goes full speed ahead.) Minkowski goes a little farther than we, for he adds yet the third spatial co-ordinate to our imaginary curve, which we had to omit because it was impossible to represent it. So he has three spatial dimensions and one time dimension—in all, four dimensions. Every "event" in our world is for Minkowski a point in his four-dimensional "world." And every happening is described by a "world-line." Even you and I would be regarded by Minkowski as a "world-line"; as a four-dimensional worm. A hermit in his cell, immured for life, would have a straight, rising world-line, parallel to the time-axis; a steamer travelling at an equable rate would have a straight world-line, sloping gently downwards. And the line of a "stunt" aeroplane? We would rather not ask what it looks like —bent and crumpled in all *four* directions!—If I go with my fiancée to the cinema, our world-lines will run side by side a little way, and then divide. And if we miss each other next time, because one or the other is unpunctual, it is only because the two world-lines have lost one another and cannot come together!



Minkowski's world-lines, which fill a four-dimensional mathematical space with their serpentine tangle, are the image of our world in space and time. We will once more sacrifice two spatial dimensions, in order to satisfy our restricted outlook, and return to the simplified world-line of the *Bremen* making a smooth, quiet passage across the ocean (see sketch). We see that every "event"—the signal on the captain's bridge-

telegraph in Bremerhaven on March 1st, or the order "Stand by to berth!" in New York—is represented by a single point on the world-line. But what is their distance from each other —the interval between two events? The spatial interval is the distance Bremerhaven-New York = 3,700 miles; the temporal interval is five days. And the "space-time interval"? It is given by the distance between the head and tail of our world-line of the *Bremen*: by its length.

That is how things appear from Germany. But how would a passenger on the *Bremen* look at the matter? Do not let us forget that as there is only one world, so there is only one "Minkowski space," and only one world-line of the *Bremen*.



But a *Bremen* passenger sees the world-lines from another angle. His field is the *Bremen*; during the whole voyage it never moves away from him —otherwise there would be a cry of "Man overboard!" For him this field is at rest. But we know what the world-line of anything at rest is like; it is a line parallel to the time-axis. The *Bremen* passenger must introduce a different time-axis, and in order that space shall be served no worse, a different space-axis. The second sketch shows the passenger's axes.

And now we perceive, to our astonishment, that the passenger is given a quite different interval between the two events, "Full steam ahead!" and "Stand by!" For him the spatial interval is nil, since for him both things have happened in the same place. Similarly, for me the spatial interval between the two events "going to bed" and "getting up" is nil, as both things have happened in the same place—although in a certain sense my bed has moved away from my bed during the night, since the Earth has carried it along on its orbit.

The *Bremen* passenger, then, registers a decidedly shorter spatial interval than the man on dry land! one might almost imagine that he utilized the space saved by turning it into time,

and so at least obtained a correspondingly greater time-interval; but this is not correct. He will perceive even the time-interval between arrival and departure as somewhat shorter, because his days are a little longer than ours, so that he does not register so many of them on the world-line.

In any case—to say it once more—the *Bremen* passenger has another spatial and temporal interval between the two things than ours on *terra firma*. Only the length of the world-line between the two dates—*the undivided space-time interval*, *is the same for both.*

When we happily and innocently look about us in this motley world, we are ruthlessly striding through Minkowski's world; we split it into its components—three spatial and one temporal. The space and the temporal interval allotted to us depend upon our velocity at the moment—upon how and in what direction we are moving—so that we must not be surprised if we are allotted a different simultaneousness to that of the Stockholm aviator, or if we see the express aeroplane contracted, and the time *in* it retarded. Here we have different sections through *one* world. But the space-time interval always remains the same—it is unalterable, an "invariable"; Minkowski describes it in the remarkable words with which he began his first lecture:

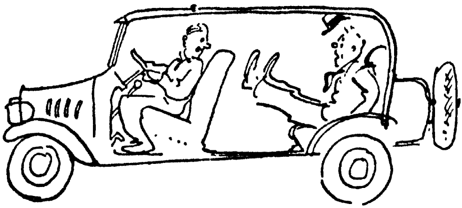
"The new theory has grown upon the solid facts. Therein lies its strength. Its tendency is radical. From now onwards space *per se* and time *per se* decline to mere shadows, and only a sort of union of the two can preserve their independence."

General Relativity

The theory of relativity as we now know it is only half a theory. Newton already realized that. We know from Michelson that an absolute velocity cannot be demonstrated. But what of acceleration—that is, an *alteration* of velocity?—We have a vivid sense of acceleration; in a car starting from rest we feel when the velocity increases; we are pressed against the cushions; and we are conscious when the driver of an express train puts the brakes on, and its velocity decreases. If we are facing the engine, we have a definite impression that we are

running downhill. This encouraged Einstein to extend his theory to acceleration. And here a little explanation is necessary.

The other day I came upon two heavy balls of metal—one of brass, one of iron. Their masses were equal. I gave each the same impetus—and they rolled across the smooth lawn. I weighed them consideringly in my hand—they were equally heavy, and when I let them fall they fell at the same rate. "This is very curious," I said. "It's a matter of course," I was told. "The balls fall because they are attracted by the Earth. Their masses are equal—so they are attracted with equal force." But I bring a powerful electromagnet up to them and switch it on. The



iron ball rolls quickly up to it; the brass ball takes no more notice of it than a dog of a five-pound note. How's this? The two balls are supposed to have the same mass. We see, then, there is something vague in the concept of mass; we treat *inert* mass and *heavy* mass as though they were the same thing; but they are not. The mass that possesses *inertia* is the only one that we recognize in physics. It resists acceleration. It is because of this mass that the locomotive has to puff and groan on setting the train in motion. The *heavy* mass acts in quite a different direction—downwards, upon the rails. It is a miracle, and nothing else, that bodies of the same mass are equally heavy—that they are attracted with equal force in the gravitational field. But this miracle has repeatedly been verified by the most delicate experiments. *The inert mass and the heavy mass of a body are equal.* From this it was only a step to the notion—but the step had first to be taken: If the inert and the heavy mass are always equal, this is no miracle, but a matter of course. We must not draw any distinction between

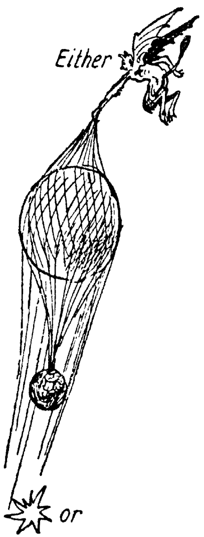
the two masses. This recognition is known as "the principle of equivalence."

Once more we will try to follow Einstein's imaginary experiment—the experiment of the boxed-up physicists. Let us imagine Professor Piccard and his assistant in their sealed gondola. High above their heads is the balloon. Let us assume that they have flown to some remote and unknown point of space. The gondola is now motionless. There is nothing anywhere near them; no star, no Earth. Nothing, that is, to exert any force of attraction. If M. Piccard wants to take off his spectacles for a moment, in order to read the electrometer, he simply places them beside him in the air, and there they remain. A glass of water remains full in any position, even upside down. It sees no reason why it should pour itself out. Piccard and his assistant, with the *savant's* carefree lack of prejudice, have quickly accustomed themselves to this state of affairs, and find it quite normal.

But suddenly the unexpected occurs: with a violent jerk the spectacles set themselves in motion, and break with a tinkle on the floor. That's that, and now, to make matters worse, the water in the glass pours over them. "Hullo!" thinks Piccard: "we have run unawares into a gravitational field! There must be some star or planet beneath us, and now everything will fall to the floor again." —"Quite possible, Professor," says the assistant. "But I'm more inclined to think that the Devil or Beelzebub has collared our balloon, and is dragging it, together with our gondola, with increasing and uniformly accelerated velocity through space. A pity that the gondola is sealed; how shall we decide, Professor, which of us is right? If you are right with your hypothesis of the star, the spectacles fell to the floor because they were *heavy*. If the theory of Beelzebub is correct, the inert mass of the spectacles resisted acceleration; they remained where they were, and

the floor of the gondola struck against them with considerable velocity."

"Oho!" said Piccard. "But now, if I were to fire a revolver-bullet sideways through the gondola, the orifice of entry will be rather lower than the orifice of exit, because the bullet will have dropped a little during its flight, and its trajectory will be curved downwards like the parabola of the jet from a garden hose."



"No, no—while the bullet is travelling the whole gondola will rise just that little distance upwards in the wake of this rushing devil."

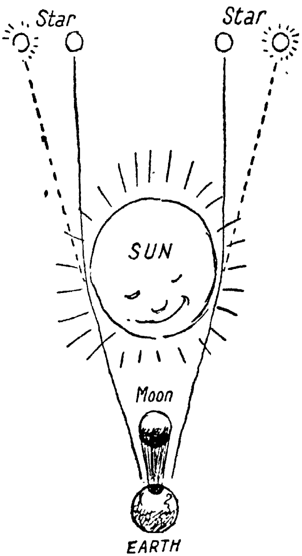
"Let's try it with a ray of light!" the Professor proposes. "If your theory is correct, the light-ray, too, will move just a little downwards. But if my hypothesis of the star is correct the light-ray will remain at the same level, since light is not subject to gravity."

They are on the point of making the novel experiment; an experiment which, like Michelson's, is to give a definite answer to the question: motion or rest? It is high time for Einstein to intervene. For he has enunciated the principle of general relativity—according to which the problem of absolute acceleration must be meaningless. Basing his statement on the equivalence of inert and heavy mass, he asserts: That it is impossible to decide whether the balloon and gondola are being dragged along or are situated in a gravitational field. Both views are equally justified —Piccard and his assistant are both right, each from his own point of view. The gravitational field is merely the equivalent of an acceleration. And the light-experiment? It would of necessity give a negative result, says Einstein. *Light is heavy* —it falls, just like a solid body—like the spectacles.

Light is heavy. Can this assertion be verified, or is it a vague and remote theory?—A way was found of testing it, and was promptly followed.

What does Energy weigh?

The Sun reaches out all round it. In the gravitational field of the Earth the deflection of light is too small to be noticed; but the Sun is a proper, steady, well-behaved star, and the bend which it imposes upon light-rays is just within the limits of the measurable. The light of a far distant star which passes close to the Sun falls just a little way towards it, like a swiftly hurled stone. The light is slightly deflected —and Einstein was able to calculate the exact degree of this deflection. One two-thousandth of a degree—a tiny angle; a match, at the distance of a kilometre, would seem as wide to the naked eye. And in connection with this infinitesimal value Einstein's theory came out of the study into the open, into the region of facts. Theoretically, this deflection could be measured to-day, or tomorrow, or at any time. But unfortunately stars are not usually visible close to the Sun. We have to wait for a while, until Nature covers the Sun up for us—until there is a total eclipse of the Sun. There was one in 1919. The British, at the instance of the Astronomer Royal, equipped two expeditions; one to Principe on the coast of Africa, and one to Sobral in Brazil. As Eddington observed, this eclipse was a lucky chance which seemed to have been brought about on purpose. For if one asks an astronomer what is the most favourable date for such a measurement—that is, when the Sun is close to two bright and suitable stars—he will reply, the twenty-ninth of May. The total eclipse of 1919 took place on this date. Not until 1938 shall we again have such a good opportunity of



testing the theory; at most eclipses the measurement is much more difficult to make.

Eclipse expeditions are peculiar affairs. They have only a few minutes at their disposal, and in these few minutes all the various manipulations must be effected with absolute punctuality. One man, for example, has the job of changing the dark slides; another sees that the heliostat is working properly (the heliostat is a mirror which follows the course of the sun); for no repetition is possible—bygones are bygones! In the four minutes of the eclipse the fate of a theory was decided at Sobral—our conception of the Universe was at stake. Two stars on either side of the Sun's disc were to be measured; and they ought to be apparently farther apart than they had been six months earlier, when the Sun was nowhere near them, and their light was not deflected.—The displacement on the photographic plates would amount to a few hundredths of a millimetre.

At Principe the weather was dull and cloudy, and only a few exposures were made; but four months later confirmation came from Sobral: the Einstein effect had been observed. The two expeditions had achieved their end; they had discovered that light is heavy. They had looked "behind the Sun." There is no denying the fact, and today it is generally admitted.—Well, light is light. Eddington has calculated that a pound of light, according to the current tariff—three halfpence per kilowatt-hour—would cost £100,000,000. Yet the Sun delivers to us daily, gratis and carriage paid, a hundred and sixty tons of light. And the weight of the Earth would increase by a hundred and sixty tons daily if it did not radiate light and heat into space, and so diminish the effect of the light received.

It is agreed, then, that light has mass; and we must not treat the other forms of energy less generously. As a matter of fact, even before he had enunciated the theory of relativity, Einstein had made the fundamental statement: All energy, in whatever form or disguise it may appear, has a certain mass. But it is not consistent with the habit of the new thought to halt half-way to the goal. So today we say: *Energy and mass are one and the same thing. What we call mass is only a new manifestation of energy.*

The mass of a body signifies a certain energy. For practical purposes it is convenient to divide the energy of a cannon-ball, representing it as the sum of the mass of the ball and its energy of motion, or kinetic energy. (We can then say: The energy of a body is equal to its energy of mass plus its energy of motion. We can also say, of course: The mass of the body is equal to its "resting mass" and the mass of its kinetic energy. Both statements have the same significance.) But this division is arbitrary and useful only for practical purposes. In the same way we can divide the property of a rich man into capital and landed property. But his fortune remains the same.

The complete identity of mass and energy is no mere crotchet of the theoreticians. It is stark, physical reality, and could be measured without more ado: there are no theoretical difficulties in the way, but only experimental. In summer a man is warmer than in winter, and therefore contains more energy. He therefore weighs more in summer than in winter, and more by day than by night. It is true that we have no scales as yet by which we could measure this difference; it would be masked by all sorts of concomitant effects. (For example, every body is immersed, in the atmosphere. In weighing it accurately we must add to its weight that of the air displaced. This is quite considerable, and the fact that the cold night air is heavier than the warm air of the daytime will of itself make a difference greater than the difference in the two weights of the body). If we melt a kilogramme of ice the water contained in the ice weighs a tiny fraction more than a kilogramme, because the water contains the energy of the heat that melted the ice.

A great step has been taken towards the unification of the Universe. The doctrines of the conservation of energy and the conservation of mass are now amalgamated, and the almost startling thought arises: Can mass be transformed into energy?

As an ordinary thing, the energy of mass is locked up—we cannot get at it. If we could only make this monstrous capital fluid we should have a wealth of energy whose effects would be catastrophic. The mass-energy of a single gramme, according to Einstein, is equivalent to 25 million kilowatt hours, or 1,000-H.P. working for four years. The pencil in my hand

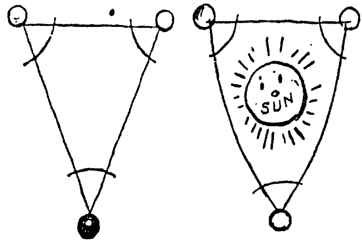
contains energy enough to fling me far above the limits of atmosphere, and out into empty space. The energy of mass of this book would suffice to drive an ocean-going steamer for one hundred years—if we could utilize it. For the time being, of course, this appears to be impossible—apart from one exception. Radioactivity is able to draw part of its energy from a process of "mass-radiation."

We will conclude with one last result: The mass—and please don't confuse mass with circumference or volume—the mass of a cannon-ball or a rocket depends on its energy. The faster the cannon-ball travels, the greater its energy of motion, and the greater its mass; and according to the formulae of the theory of relativity its mass will become *infinitely* great if the cannon-ball attains the velocity of light. Not all the force in the Universe would then suffice to accelerate it in the slightest degree. And this law could be verified by experiment—not with cannon-balls, indeed, but with electrons, which can be accelerated, by tremendous electrical potentials, until their velocity approaches that of light—but then the mass of even these tiny electrons would become too enormous, so that millions and thousands of millions of volts could not make them *quite* reach the velocity of light, or exceed it.

"Couldn't it exceed it by the tiniest little fraction?"—"No," say the formulae, sternly and inexorably. "But you have no cause for complaint there. 300,000 kilometres per second is quite a good velocity. Never has matter or energy moved any faster, and never will it do so!"

The New Theory of Gravity

It would be more correct to say: The first theory of gravity. You will be told that Newton enunciated a theory of gravitation, but he only stated the law in accordance with which two bodies attract each other; he did not say *why* they attract each other. In one of his letters he writes: You say that the weight of all matter is inherent in it and essential. Pray do not believe that I have exact knowledge of this; for this is the very claim that I do not make, that the cause of gravitation is known to me. To ascertain this would demand very much more time.



Do we know it today? Consider light: we can explain most of the practical achievements of optical science—telescope, speculum, camera—once it is granted that there are light-rays in the Universe, which can be refracted and reflected in accordance with certain laws. But who would claim that we today, even after the publication of Maxwell's electromagnetic theory of light, know more of the nature of light than the maker of the first telescope?—It is the same with gravity.

We know by long experience that light travels in straight lines. But what is a straight line? Think of the edge of a nice smooth ruler; or a stretched string, with which the gardener is marking off a bed; you give it a scrutinizing glance, and say: the string is straight. Now let the gardener, with a light-ray, mark out a gigantic bed in space, a huge triangular bed, with the Sun lying in the middle of it, just for ornament, Ah, we can guess already what will happen: the light-ray will be a little bent in the neighbourhood of the Sun. The edges of the poor fellow's bed won't be straight! We could photograph his work. We might then remove the Sun and ask him to do his

job again, and we might photograph this too. The two photographs would be different. The expedition to Sobral in 1919 proved this in black and white. Nevertheless, the gardener would declare that your reproaches were quite unjustified; he did exactly the same thing in each case—exactly what he had been taught to do: he couldn't see that the bed with the Sun in it was curved in any way; we had better look at it ourselves. So we go and examine it ourselves, taking sights along his lines of pegs. He is quite right: they are all in line.

This is enough to make anyone angry. We don't give up until the mistake is explained. We stare at his pegs for half a year, until the Sun is far away; but they are still correctly in line. The gardener is right!

We will hope that he is an uneducated gardener, without preconceived opinions, and that he sets no particular value on such notions as the deflection of light, the mass of energy, and the like.

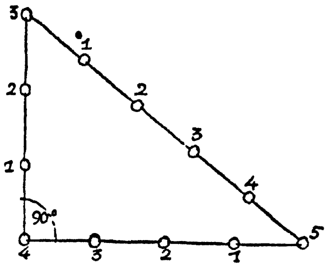
"The sum of the angles in your triangular bed is too great when the Sun is lying in it!" we say. "It ought to be 180°!"—"Why?" he asks.—"Because Euclid has proved it!"—"I know nothing about Euclid, and it's not for him to give me orders. The main thing is—my bed is properly marked out. And I think it looks fine with the Sun in it."—"But then you must be living in curved space!" we cry in dismay.—"Well, why not?" says the gardener, who cares nothing for such things.

Well, he is in good company. For example, he could call upon Carl Friedrich Gauss to support him.

Why do we always bow down to the name of Euclid? Because his geometry is the only conceivable and rational geometry? Kant thought so. But in the meantime the mathematicians—Bolyai, Lobatschewski, Riemann—have propounded other geometries, whose hypotheses differ somewhat from those of Euclid—for example, they discard the axiom of parallels, yet in themselves they are logical and consistent. Euclid proceeds from certain "intuitive" principles, incapable of further demonstration (axioms)—as, for example, that I can draw, through a point, only a single parallel to a given straight line; but this axiom has been strongly disputed, and not only in recent years. There must be something different! Perhaps the

name "geometry" will help us—"earth measurement." It was by the measurement of the soil that Euclid's laws were discovered. The Egyptian surveyor, when he wanted to lay out a right angle, used a measuring-chain with three, four, and five knots (the doctrine of Pythagoras!) Terrestial, solid, rigid bodies, we may say, obey the laws of Euclid.

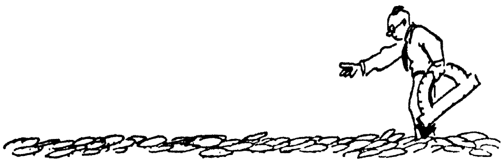
But the theory of relativity has made a clean sweep with this concept: There are no rigid bodies: all bodies are subject to the Lorentz contraction! Today we have Euclidean and non-Euclidean geometries, and our accuracy of measurement has considerably increased. This is reason enough to distrust the old geometry. And we have only one way of deciding which of the many geometries we should adopt: to do what the Egyptians did—repeat our measurements! As long ago as 1840 Gauss saw that this was necessary. He measured a great



triangle on the North German plain—Inselberg, Brocken, Hoher Hagen—as accurately as he could. He found, within the limits of his coefficient of error, the 180° which Euclid required. He was probably rather disappointed. It would certainly have pleased him better if he had obtained a larger sum than this dull and hackneyed figure—when he could have declared that a non-Euclidean geometry was physically real, thereby liberating it from its shadowy unsubstantiality. Gauss never published his measurements; he "feared the outcry of the Boeotians." But need we therefore lose heart? We will simply say: Space is approximately Euclidean—just as a sufficiently small portion of the Earth's surface is flat. And you see, our optimism was justified. The British astronomers at Sobral repeated Gauss's experiment in space, and they found, as our gardener found, that the geometry of Euclid does not hold good in the neighbourhood of the Sun. The Sun's great mass modifies the geometry of the region. If the mathematicians had hit upon some other expression, very

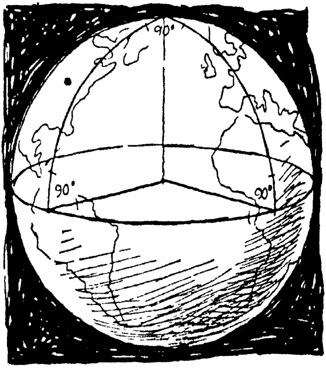
probably no one would have raised any objection to it; but unfortunately what they said was: Space is *curved* near the Sun.

But what does "curved space" mean? We have already explained: it means simply this—that any experimental measurements which we may make do not everywhere obey the laws of Euclidean geometry, but they do obey other laws. —Let us imagine that we had opened a school of mathematics for bugs—or for sheets of paper—flat, two-dimensional beings, *absolutely incapable of spatial notions*. And we will imagine that these thinking bugs, or sheets of paper, wandering over a great sandy desert, flat as a table, assembled in front of us—at our feet, so to speak—in order to hear something about "general



cosmology."—"I have now explained to you the fundamental notions of geometry. Go and see whether they are correct—whether Euclid is right." So they dispersed into the desert, measured circles, triangles, and angles, ran about with theodolites and surveying instruments, wrote their results on their tablets, and returned with a satisfied air. "We have all made our measurements. Euclid was right. The sum of the angles of a triangle is 180°. What other result would be even conceivable? Our philosophers told us long ago that only a flat, Euclidean space was thinkable. They warned us that a few crazy mathematicians were haunted by the idea of a three-dimensional something, but that, of course, is mere twaddle." I smiled. How easy it would have been to lift one of these beings a fraction of an inch above the sand of the desert *into the third dimension*! For his companions he would have disappeared, as though he had been spirited out of existence. But I held my peace, and was just about to begin my lecture when three bugs came pushing their way through the ranks of their fellows, wildly waving their fore-legs, with every sign of excitement.

"Do you know what we have found? The sum of the angles is 270°!"—"Impossible!" the others vociferated. "Show us your results! How could that be? Preposterous! Ridiculous! *Inconceivable*!"—"Softly," I said. "What sort of a triangle did you three measure?"—"I stood at the North Pole."—"I was on the Equator, in Ecuador, South America."—"And I in the Cameroons. A magnificent triangle. No one can pick holes in our results—they are correct!"—And they were right; a triangle, so measured on the globe, *has* three right angles. "You see," I said, "you must get used to the idea that your world isn't flat; that it is curved. For large areas Euclid's geometry is no longer valid. The mathematicians know which geometry is really the right one for you: a 'spherical' geometry. And you see—you have to measure large areas before you realize it. You are living in a curved world. Understand it if you can."—The uproar increased.



I am afraid we must blame the bugs; they were, of course, too superficial in their measurements. If they had measured not only the smooth desert, but the whole surface of the globe, with its mountains and valleys, they would have shown that their world is not only curved as a whole, but that in their own region it is more curved than elsewhere.—They are not very bulky, when we consider the globe as a whole, but they do exist.

If I asked the bugs to draw me a straight line, they would fulfil their task conscientiously, and measure a straight line from North to South, along the meridian circle. For them the straight line from Brieg to Domodossolo would run over the mountains, not through the Simplon tunnel; since this latter would be, for them, a path in the third dimension, which to them is simply impossible. So they will clamber over the peaks

and precipices of the Alps, and really find the shortest way that can be found over the mountains. But if I tell them that there is a shorter way, a direct connection between the two localities, they will decline to consider my transcendental, "metaphysical" speculation—they have already discovered the shortest way! In mathematical parlance, they have traced a geodetic line. A thread tightly stretched from place to place would run along a geodetic line if the line lay on the level all the way. Now add but a single dimension to the world of the bugs, and you have the image of our space. Our space, too—says the

general theory of relativity—is everywhere curved; that is, the Euclidean geometry is not valid for it. Actually the four-dimensional universe of Minkowski is the culprit. This is curved, and our space, which is only a section through this Universe, must of necessity be curved also. In many places the curve is exaggerated, making a little hill, and there is a sun, a star: matter.

We go for a stroll, and come to a place where the molecules are tearing about in rapid zigzag motion; and we say: it is hot here. We don't ask how the heat contrives to set the molecules in motion: the motion of the molecules *is* the heat. If we wander about the Universe we come to a place where the ether is in a peculiar state of rapidly alternating electromagnetic tension, and we say: Here is light! But we don't ask by what artifice the light contrives to put the ether into this state of oscillating tension; for this condition *is* light.—We wander on

and come to a place where space is more strongly curved than elsewhere. We do not ask further questions: we call this curvature matter.

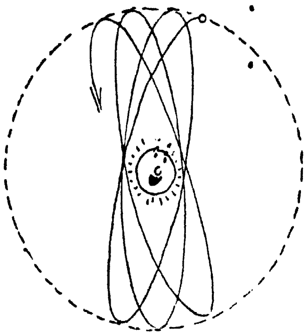
The rest is soon said. If space is curved, then what we have always called a straight line is only a "straightest"—a "geodetic" line. A being who looked down on us from his four-dimensional world, as we look down from our space on the two-dimensional bugs, would be able to effect a shorter communication, but it would have to be in four-dimensional space—that is, it would have to lead *out of our Universe.* A free body, which is not impeded by friction or similar forces, flies through the Universe along a geodetic line. This is the natural generalization of the law of inertia. Light moves along a geodetic line; if we throw a stone it flies along a geodetic line; a meteor rushing through empty space follows a geodetic line; the Earth travels through the solar system along a geodetic line; and because the curvature of space is enhanced in the neighbourhood of the Sun—and the whole planetary system, measured by cosmic standards, lies in the immediate vicinity of the Sun—the geodetic line has there become an orbit.

We no longer need, as Newton needed, a mysterious force—"gravitational force"; all we need is to discover the law to which the curvature of space is subject. Of course, this task, however simple it may sound, is one of the most difficult mathematical problems imaginable. The mathematician speaks of "tensors" and such things.

The new theory of gravitation, which is based upon the hypothesis of transmitted action (Newton's, of course, was based on the hypothesis of action at a distance), leads us into difficulties of which former generations had hardly a premonition; but it also leads, or so it seems to us, to a new and profounder understanding of gravitation—to an understanding of the essential nature of space and the general structure of the Universe.

So it is not of such decisive importance that it differs—except in the case of the curvature of light—only in respect of a few insignificant conclusions from the Newtonian theory; though, of course, it is highly gratifying that in these it hits the nail on the head. One of these conclusions relates to the

rotation of Mercury's orbit. Mercury revolves in an ellipse, which has the Sun at one of its foci. But this elliptical orbit is not fixed in space, for the ellipse itself revolves slowly round the Sun—once in three million years; so that the actual path of the planet is a sort of rosette. This little deviation is an unexplained defect of the Newtonian theory. For a long while it was believed that a smaller planet, revolving close to the Sun, was the disturbing element; the astronomers tried to calculate its orbit, and even a name was kept in readiness for it: Vulcan. But the name will never be used, for there is not, and never will be, a Vulcan.



Instead of Vulcan we have a general theory of relativity, from whose equations this infinitesimal rotation follows as a matter of course: follows as a subsidiary result, although Einstein, in working out his equations, was assuredly thinking of neither Mercury nor Vulcan.

The other conclusion refers to the "displacement towards the red" in the lines of the solar spectrum, and in the spectra of all other heavy stars. Light uses up a little energy in escaping from the gravitational field of the Sun, and so becomes a little redder, its wave-lengths a little longer. According to the most accurate measurements, we must now accept the fact that this displacement does really occur, but it is very near the limits of the imperceptible.

However, we will concern ourselves no longer with these infinitesimal matters; but go on to consider the terrific and menacing facts revealed by the new giant telescope of the Mount Wilson observatory.

Finite Space

Once more we must return to our bugs.—"I have proved to you," I say, "that you are living in a curved world." (General

uneasiness.) "And further—your world is actually—finite!" (Flat contradictions, and hisses from individual members of the audience.) "I have sent two of your comrades on a long journey—they are to travel straight on, always following their noses, without turning either to the right or the left. They set off into the West—and there they are—they are coming now!" And in the East appear two tiny dots, which gradually increase in size: the two world-wanderers, who have made the circuit of the globe. They are tired and dusty. They swear a thousand oaths that they departed neither to the right nor to the left of a straight line.—"You see—every straight line returns upon itself! Your world is finite! And that's enough for today." —Squabbling, arguing, exasperated, my audience disperses. "Crazy—impossible,"—I hear them say; and then the louder voice of a single bug who has some notion of the general theory of relativity: "Why impossible? Isn't a limitless but finite world a matter of course? My theory presupposes it—I can even calculate the radius of our world and its magnitude!" —And they go their ways.

The ancients believed that the Earth was a flat disk. But they also believed in Euclid's geometry. If they had tried to verify this by measurements they might have found that the Earth is less generous than Euclid. It doesn't place as much room at our disposal as Euclid demanded. I can stand at the North Pole and from that point describe concentric circles on the great "flat" waste of ice—as though I were making a gigantic target. The circles grow larger and larger. A circle 1 kilometre in diameter has a circumference of 3·14 kilometres; that is correct. But a circle whose diameter—measured on the Earth's surface—is 12,400 miles is not 38,946 miles in circumference as Euclid would have it, but only 24,900 miles; it is the Equator.

This is obviously in contradiction to Euclid. Today we know that the Earth is a sphere, and Euclid has nothing to say about the surfaces of spheres; there "spherical geometry" holds good. By its regular curvation the Earth is able to *close* itself, and so avoid any "end" or "edge" of the world. All straight lines proceeding from the North Pole intersect at the South Pole. In the end they all return upon themselves.

It looks exactly as if space were sacrificing Euclid in order to save room. I might describe spheres about Berlin as their centre. A sphere of one mile in diameter has 3·14 square miles of surface. But a sphere which is a hundred million light-years in diameter has a considerably smaller surface than this Euclidean formula would allow it. We can't, unfortunately, measure it, but today we take it on trust. Space "contracts more and more into itself" the farther we penetrate into infinity. All the straight lines that proceed from Berlin, like the spines of a huge hedgehog—*spatially* straight, of course, straight in all three directions—run together again "over there" on the other side of space, and all straight lines finally turn back to Berlin. So, just as the Earth contrives in two dimensions to close itself again by regular curvature, so space contrives to avoid any "end" of space, and the Universe to enclose a finite content. The diameter of the Universe amounts —or rather, at one time amounted—to 2,000 million light-years. This, then, is on principle the greatest conceivable distance in our Universe.

The absolute "spherical space" of Einstein, as here illustrated, is not only a rather spookish thing in itself—it also contains real spooks—phantoms of stars and nebulae. For every light-ray that fares forth into space must eventually return upon itself.

Light takes 6,000 million years to make the circuit of the Universe, and in a spherical space it would be conceivable that only a certain proportion of the stars which we see in the heavens were genuine—that the rest were ghosts, phantoms, images of the same stars—light that was emitted 6,000 million years ago, the witness to their past. We have only to go out of doors and look straight ahead. If we waited for a while we should suddenly see before us the image of the Earth and the back of our own head—and it would not even be a faint image, for spherical space should act like a mighty lens, collecting and returning to us *all* the light emitted from the back of the head. We should have seen round the Universe. But we had better take a camp-stool if we are going to wait until then, for we shall have to wait some time—we shall have to wait 6,000 million years.

As a matter of fact, however, the light will be slightly

deflected, on its long journey through space, by the stars which it passes—it will lose its way, and the light-rays will miss their aim, so that the image will be much too vague and indeterminate to recognize—indeed, it will not be formed. A pity!

Hidden in spherical space, we sit at our telescope and scrutinize the Universe. We do not see much, even with our largest instruments; only a tiny bit of the Universe, as large, in proportion to the whole, as France in comparison to the whole globe. Farther and farther our straining eyes reach into the unfathomable. In the profound, menacing blackness of the heavens the stars are immeasurably remote. In a sweeping curve the shimmering track of the Milky Way intersects the dome of the skies. So empty seems the space around us, so immeasurably great and empty, and yet we know that all these distant wonders are our nearest neighbours. An island, a flat, lenticular disk in space: a densely populated, congested community of 100,000 million giant suns, fleeing from the greater, remoter void without—that is the Milky Way, in which our Sun has its place.

Far beyond its limits lie other systems, other Milky Ways, other islands in the void. Their total number is estimated at 100,000 millions. We see them as spiral nebulae, as radiant wheels of light; as our Milky Way would appear if seen from above.

Ten million million—ten billion—kilometres is the distance travelled by light in one year; over six million million miles. But it takes millions of years to reach us from the spiral nebulae—indeed, the last visible nebula is 150 million light-years away, a pale, faint speck of dusty light. In the last few years we have succeeded in bridging even this terrifying space of nothingness, the space that divides us from the spiral nebulae—since the Mt. Wilson Observatory in California has housed the gigantic telescope with the 2½-metre speculum. A miracle of science and technique, this giant speculum; incredible precautions had to be taken during its manufacture; the glass, after casting, had to be cooled with almost imperceptible gradualness—for months on end the temperature was cautiously lowered, degree by degree.

But when we scan the heavens with this magic instrument

—when our eyes see more and more keenly—we suddenly start back in alarm; the spiral nebulae are running away!

Let us see what it all means. The title of this section may appear rather mysterious:

"Displacement towards the Red"

In the beginning . . .

There was no talk of Man as yet. Dragons pushed their uncouth, scaly bodies through the brittle, overgrown ferns;

a moist, brooding, hot-house mist covered the Earth, which was rarely enlivened by a ray of sunlight. It was about a hundred and fifty million years before our days.

About this time a warning was spoken in the star-cloud in the Twins, far away in the Universe: Look sharp if you want to get to the Earth in time! And the whole swarm of atoms —calcium, helium, hydrogen, iron—began to radiate with one accord. It is doubtful if they were conscious of their importance. After all, ever since they could remember, they had never done anything but radiate. But just at the very moment when the Plesiosaurus popped his head above water—a wicked little head on an endlessly long neck—the fateful hour struck for the light-waves of Neb. Z. "One day you will have to give an account of our star, of your home. Be good—don't disgrace

us. And pay your respects to Mr. Humason in California." The light-waves hadn't a notion who Mr. Humason might be —indeed, they couldn't have known, for there was no America as yet. But they wasted no time in thinking; they rushed off then and there, through the dark, unspeakably empty space of the Universe. Years, centuries, hundreds and thousands of centuries passed. The dragons vanished, and so did their successors; the face of the Earth was changing. The glaciers of the Ice Age crept downwards from the north and buried the land under their icy covering; and they melted and disappeared, leaving behind them only great heaps of rock—the moraines. And Man appeared.

The light-waves hurried through space; every second saw them 300,000 kilometres farther on their journey. Under the whips of their overseers the Egyptian slaves piled up the monstrous stones of the Great Pyramid; and slaves and overseers and kings lived and died and were forgotten.

America was discovered. In Europe Newton, Kepler, and Copernicus were born, who sought to make the heavens subject to their science. Galileo searched through the starry universe with his telescope, Olaf Römer measured the speed of light, Herschel built his reflecting telescope, Bunsen and Kirchhoff developed the method of spectro-analysis. Of all this the light-rays knew nothing. They hastened, rigid and unmoved, through the darkness of space; and then, at last, far in front of them, a tiny point of light appeared. This was their goal—the Sun. A star of the sixth magnitude. And with renewed courage they shot onwards, always at 300,000 kilometres per second. They came to the last milestone, the star Alpha Centauri. "To California 4 years" was written on it in great letters. "Hurrah, boys!" cried the ever-cheerful calcium light. "On we go!" Bigger and bigger grew the Sun, brighter and brighter it shone in the black heavens—small, and almost invisible, twinkled the home which they had left

a hundred and fifty million years ago, the star in Neb. Z. And there was the tiny, pigmy Earth, revolving round the Sun with a motion that seemed to them unnaturally slow. They were there!

On the Earth all sorts of things were happening. Earthquakes, conferences, the "shooting" of films, horse-racing, boxing contests. And one fine day Mr. Humason, in the Mt. Wilson observatory, asked a question: "What's on today? Neb. Z—all right. Have the big reflector and the spectroscope got ready, Nelson." And Mr. Humason went to bed. He rose again at midnight, and now he stood in the dim light of the great dome. The slit-like opening was uncovered, the night was clear and fine, and the lights of Los Angeles twinkled in the valley.—"Ready?" he asked. "All in order?" About this time the first light-rays were crossing the orbit of Jupiter. Massive and silent, the tube of the great telescope pointed upwards. One could hear the faint hum of the motor that rotated the telescope, evenly and without a tremor, in the opposite direction to the rotation of the Earth, swinging it from East to West, following the stars in the heavens, lifting it slowly to the zenith and lowering it again. Cold and menacing, the huge and precious speculum, two and a half metres in diameter, gleamed at the bottom of the tube; small and curiously compressed, like a misshapen dwarf, the spectrographic attachment squatted on the eyepiece. The astronomer glanced through the finder. How well he knew every part of the heavens, and yet never well enough! "Here goes, then!" And he drew back the shutter of the dark slide. The light-rays were crossing the orbit of the moon as the astronomer drew the shutter. And they were here almost as soon as the plate was fully uncovered—they shot through the tube, and fell upon the concave speculum. —They who had raced through space for 150 million years, always in a straight line, now allowed themselves to be turned back by a piece of glass. Obediently following the path prescribed for them in the telescope, they fell, compressed into a pencil, on to the few square inches of the photographic plate which stood in their way, and they began their work—the chemical modification of the light-sensitive film. All night long the rain of light-rays poured through the wide-open mouth

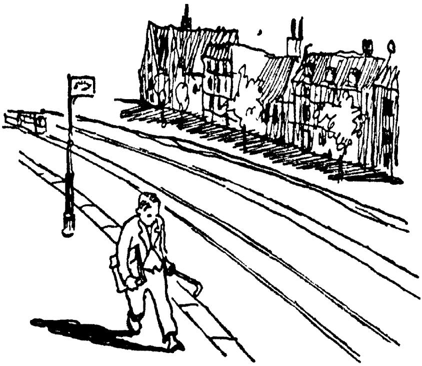
of the giant telescope and fell upon the little plate; then, shortly before daybreak, before the first signs of the morning twilight, an alarm-clock shrilled, and the shutter of the dark slide closed of itself. In vain the light-rays from the distant star beat upon the observatory—they found the doors closed against them, and perished miserably. It was too late. They were a minute late on this journey of millions of years. They could no longer contribute to human knowledge.

But Humason cared for none of these things—he removed the dark slide, took it to the dark-room, and developed a few lines on the plate. The light of the stars—the lines of the spectrum! (See p. 234.) He knew them well, these lines. Nebula Z contains calcium, hydrogen, helium—it's always the same everywhere! Nothing new in the Universe! Only—the lines were "displaced." They were not in the places which belonged to them; the well-known yellow D-line, the sodium line, was nearly deep red. This, after all, was something, and Humason gave a satisfied nod. He knew why the line had moved. The nebula had gone a-wandering; at the time when it radiated the light, when the dragon popped his head out of the sea, it signalled that it was rapidly receding from the Earth. The "displacement towards the red" told him so. But how?

Suppose you are waiting for the tram. Naturally, it has just gone. Now, in physical terms, a tramway is a periodic event with a frequency of ten minutes—for every ten minutes a fresh tram comes along—and it doesn't really matter which particular tram-car I travel by. But we'll say that at 12.0 noon I have lost my tram from the town hall; it's a gloriously fine day, and I decide to walk into the city until the next tram overtakes me. When will that be? In ten minutes? Obviously not, for the tram doesn't reach the town hall until 12.10, and now it will be two or three minutes before it overtakes me, as by then I shall be several stages nearer my destination. In other words—the temporal interval between two trams becomes longer for me if I "recede" in front of it. The frequency is lower.

My friend, who was in the same case, decided to walk towards the tram; he met the same tram, not at 12.13, nor yet at 12.10, but a few minutes earlier, say at 12.8; and riding back in the tram, he reached the town hall at 12.10, and my

stopping-place at 12.13. For him the next tram appeared after only eight minutes—for him the frequency had increased. The analogy is easily grasped. Suppose a violinist, standing beside you, keeps on playing an "A." The "A" is a periodic event—sound-waves of a definite frequency. But now you jump into a motor-car and drive away from him, running away from the sound-waves. You won't hear A any longer—you will hear a deeper note. And if you drive towards the player,



you will hear a slightly higher note, because the frequency of the waves will have increased. The next vibration of the air reaches your ear just a little too soon, because you have gone a little way to meet it. Evidently the same thing would happen if you put the violinist into the car while you yourself stood still. While he was approaching you he would apparently be playing flat. These two cases are not mere theory—with a little attention you can confirm them for yourself—whether you pass a factory in an express train while the factory siren is sounding, or whether you are overtaken by a whistling locomotive or a hooting motor-car. There is always the same apparent change of tone—the shift of pitch, of frequency. It is known as the "Doppler shift", or "Doppler's effect," since the physicist Doppler was the first to detect it.

"Doppler's effect" leads us, in strict logic, to draw some strange conclusions. If we are following the line of the tramway

it seems to us a matter of course that the frequency will fall to zero if we ourselves move as fast as the trams. It is obvious that then no cars can overtake us—and we should certainly be surprised if when we were unsuspectingly riding on car 177, a second 177 were suddenly to come up behind us, and drive past us with a disdainful smile!

Such things don't happen. But if we apply this principle to sound, it means just this: If I travel away from the violin with the speed of the sound-waves, I shall hear nothing. The new super-aeroplanes have attained to almost two-thirds of the velocity of sound-waves. When they are half as fast again we shall not hear anything of them until they are upon us, until the roar of the thousand-norsepower motors suddenly bursts upon us and sinks down into silence. To the pilot every sound from the world before him will seem unnaturally shrill and twittering, as though a gramophone record were being played much too fast, and everything will fall absolutely silent the moment he has passed it.

But this is what interests Mr. Humason, and us: Light is an oscillatory process like any other. Therefore light must show the Doppler displacement. The light from one and the same source, whether this be a searchlight or Nebula Z, must seem to oscillate rather more rapidly if that source is moving towards me—and it must undergo a shift to lower frequencies, a displacement towards the red, if the source of the light is receding from me. The shift, of course, is slight so long as the velocity is small. Stark—the German Nobel prizewinner, who won fame by discovering the "Stark effect," the modification of the lines of the spectrum in an electrical field—has actually measured, by means of the shift towards the red, the velocity of the tiny little ions, the "channel rays," in vacuum tubes; and by the same method Humason is able to determine the motion of the giant suns which are millions of light-years distant in space. Both ions and suns are subject to the same laws.

The spiral nebulae are unanimously running away from us. They are fleeing from us, but not like criminals running from the police, for the farther they are away from us the faster they travel. And they are fleeing fast—the remotest of the nebulae

increases the distance between us by 16,000 miles every second. These are uncanny velocities—even the astronomers find them uncanny; they cannot explain why a nebula should go tearing through space at such a rate—quite apart from the fact that we cannot really say *where* the nebulae are trying to go, since space, after all, is said to be closed! So we say, today, that they are not racing through space at all—space itself is running away with them!

We know that according to Einstein we have to imagine space as a sort of super-sphere. But Friedmann and Lemaître have shown that such an "Einstein universe" cannot exist; it is unstable; it must immediately begin to expand or contract. And it seems as though the Universe had elected to expand. In this it approaches the type of universe suggested by De Sitter. Like a soap-bubble, like a great toy balloon, growing ever larger and larger, so the Universe is expanding. You have seen toy balloons with advertisements printed on them. Well, the individual letters of the advertisement are growing farther and farther apart. But *we* are the letters—our Milky Way and our spiral nebulae. So it isn't the Earth that is the cause of offence—every nebula is fleeing from every other!

That is the latest notion. We can't really say that it has been absolutely proved; but the shift towards the red speaks plainly enough, and we are strongly inclined to regard it as the red rear light of a departing nebula.

The force of gravity seeks to hold the Milky Way together. There is a force which works against it, a general force of repulsion in the Universe. Long ago the two forces may have preserved equilibrium; then the Universe was at rest. But since then the force of repulsion has won the upper hand, and the force of reciprocal attraction is growing weaker and weaker as the galaxies move farther apart. More and more surely it is being overcome by the force of repulsion; wilder and wilder is the flight outwards. So swift is this flight, so headlong, that it greatly perplexes the scientists. Hitherto, in their theories concerning the age of the Universe, they have had no need to be sparing of time. A few millions of years was neither here nor there. But now, since we have learned that the nebulae are in flight, now, since we know that the radius of the Universe

is doubled every 1,300 million years, we can no longer deal with the ages in so arbitrary a fashion.

Today we are receiving light-messages from the spiral nebulae, but a time will come when they will flee faster than light can follow. Then no nebula will ever learn anything of any other nebula; for all time they will be cut off from one another. Each galactic system will continue to hold together, but the most gigantic telescopes will show us nothing outside our own galaxy, our Milky Way.

The Universe is expanding. After millions of years there will be nothing but a vast, closed Space—with tiny, lost fragments, the galaxies, drifting through it. Each will be alone; one here, one there; lost, forgotten phantoms in wide, empty space.

PART FIVE

LIGHT-QUANTA

LIGHT-QUANTA

"There was once a light-wave"

RARELY can a physical theory have seemed, at first sight, so monstrous and revolutionary as the theory of relativity, with its mysterious and grandiose epilogue of the nebulae in frantic flight from one another, its denial of absolute simultaneousness, and its assertion of the essential relationship of mass and energy. It is, to be sure, a theory full of intellectual audacities, an inconsiderate theory; but it is, physically, a logical development from the old concepts. As though the spirit of the classic physics were bent on crowning the nineteenth century—a century of impetuous development—with one last effort—as though it had wished to reveal the sum of its methods and its possibilities in one comprehensive survey, the final turret of the theory of relativity was erected—no philosophy, but merely a physical theory.

It has enabled us to formulate the laws of Nature in a more general fashion than was possible before. In certain boundary cases it predicted results which were not exactly those of the old physics—and experiment showed that it was right. When the physicists had brought their science into harmony with the requirements of the new theory—which they did most successfully—they contentedly surveyed their work, and rejoiced that they knew so much. If we rejoice today, it is only because we have seen so plainly that we know nothing.

What does the Universe look like today, so far as we can judge? The material of the Universe is matter: atoms, little discrete particles in empty space, each living its own life. Rutherford has succeeded in analysing still farther the structural details of the atom, revealing to our astonished eyes the whirligigs of positive and negative electricity. Even electricity is built out of atoms. There are electrons and protons (as well as a few positrons); but the effects of electricity are convincingly obedient to Faraday's and Maxwell's field-theory. Maxwell's theoretical prediction of electrical waves (which were then discovered by Heinrich Hertz, and which today

travel all over the globe as radio waves), and his explanation of light as an electromagnetic oscillation, was a magnificent achievement. The many experiments carried out by Young and Fresnel, the "bright shadows" of Poisson, and the diffraction-grating, prove eloquently enough the oscillatory nature of light. But our knowledge of light is still very defective. To be sure, we have a biography of light, a description of its life, which has at least the merit of brevity: namely, Maxwell's equations. They tell us that light is an electromagnetic oscillation; they give us also, if we know how to read them, information concerning all the vicissitudes—such as interference and diffraction—which a light-ray encounters during its life; they tell us what happens to a light-ray in a microscope or a camera; in short, they tell us everything that may happen to a light-ray. But when we turn back to the first page of the biography, full of curiosity as to the origin of light, we are grievously disappointed: the first page is missing!

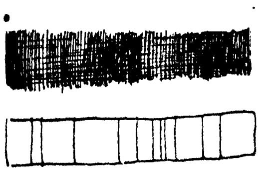
The biography begins at once with the story of the adult light-wave. "There was once a light-wave. . . ." At most there is a covert allusion to a somewhat obscure origin: "It was born of an atom." The light-wave walked out of the atom, and the door closed behind it. But we want to know exactly what happened behind the closed door. How did the atom generate the light? It is pardonable curiosity on our part if we want to know something about this creative process, and inquisitively turn to the first chapter. For it seems to us that the most significant thing about light is that it can be newly created. We do not have to fill a candle, an electric bulb, with light—as the men of Gotham wanted to fill their town hall with bucketfuls of light. The light is simply newly created.

Well—how does light come into existence? What is known of it? Who knows anything about it? Let us go straight to the right people, the spectroscopists.

We know, of course, that the spectroscopists, the "optical

tea-tasters," are following the example of Newton. They decompose the sunlight—for example—into its colours—by a prism, a grating, or other interference-apparatus; and they obtain a beautiful band of many hues. Every part of this band has a different shade of colour—a different wave-length. But they are not obliged to take the sun; all solid or fluid incandescent substances give such a band of light, a "continuous spectrum," when their light is examined through the spectroscope. In the luminous picture which they paint all the colours are blurred; they pass into one another without dividing-lines.

There are painters who paint in this fashion—with all their colours melting into one another. Other painters, the Impressionists, lay their touches of colour side by side, each distinct and separate from the rest. There are such impressionists in physics also: the gases and vapours.



An incandescent gas—for example, a neon lamp—does not emit a *band* of light; if we ask a spectroscopist to decompose its light he obtains a "line spectrum": a series of separate coloured lines, lying neatly side by side.

If we sprinkle some cooking-salt into a gas-jet the gas lights up for a moment with a brilliant yellow flame. Whenever a trace of sodium vapour is shining in a flame, or when it is made incandescent by electricity, it always emits a warm yellow light. If we let the sodium light fall on the slit of the spectroscope, what do we see? A bright yellow line. Its wave-length is about $0 \cdot 59\ \mu$. This yellow line—a D-line, it is called—is a sort of *Leitmotiv*, an infallible clue. Winnetou was a great tracker, and Sherlock Holmes, having glanced at the mud on the boot of a murdered man, could tell you the whole history of his grandmother. A lump of earth, a bent twig—and the spectroscopist knows where he is. He needs only a bright yellow streak, no matter how fine it is, and he knows with absolute, hundred-per-cent certainty—here is sodium! Doubt is out of the question. Wherever the yellow line appears in a flame, sodium must be present; no matter how it disguises itself, no matter how it hides itself, no matter how small the

quantity. For no other element—and this is the important point—no other element than sodium radiates this yellow line with the frequency of $0 \cdot 59\,\mu$. It is an infallible sign. The amount of sodium that suffices to cause a D-line is incredibly small—a millionth of a milligramme.

Bunsen and Kirchhoff made this discovery—and thereby became the founders of spectro-analysis. Every element gives different lines, a fresh "line spectrum." If we measure the lines we know the element. The number of lines, and their wave-lengths, are quite different for every element. A hydrogen atom gives only four visible lines. The best-known of these is the red line of $0 \cdot 65\,\mu$ wave-length; the $H\alpha$ line. Many thousands of lines are emitted by incandescent iron vapour—but they too are characteristic and occur in definite order. The scientists have done their utmost to measure the wave-lengths of the lines with ever-increasing accuracy. For this purpose alone the most wonderful interference-apparatus was invented; for this purpose Rowland engraved his diffraction-gratings with incredible accuracy. And today we know the wave-lengths of the lines to within a few billionths of a centimetre; an accuracy as great as though we were to measure the distance from London to Paris within a few millimetres. This is what spectroscopic accuracy means! The physicist can depend on such figures.

The Laboratory in the Universe

Fraunhofer was the first to discover certain defects in the complexion of the Sun—black, vertical streaks in the variegated band of its spectrum. Now, this is simply a negative—it looks like a negative, and it is the photographic negative of a line spectrum.—You know what happens when you print a photograph from a negative, On the plate the sky is black, faces are black, and a black coat is white; the black parts absorb the light, the translucent parts let it pass and blacken the paper, so that in the finished print the black coat is black, while people's faces, and collars, and the sky, are nearly white.

If atoms are able to emit light they must also be able to swallow it up. Let yellow light fall on a sodium atom—it simply absorbs it. On some later occasion it will re-radiate the same light. This means that if we send white light through sodium vapour, most of the light passes through it undiminished—apart from dispersion. But in the yellow part of the spectrum there is a fine black line, a gap—just where the yellow D-line is generally to be found. This is a negative; or, to put it more accurately, an absorption-spectrum. The spectrum of the Sun shows an enormous number of such absorption lines. We assume that the white-hot interior of the Sun is radiating a bright, "continuous" light, and that of the atoms in the solar atmosphere, which surround the core with dense clouds of vapour, each absorbs its special light, leaving only a tattered, imperfect remnant.

But the expert can read a negative as well as a positive. If a notorious rogue is a regular pedlar of ladies' stockings, the police will at once think of him if a number of stockings have been stolen. The "stolen light," the black lines, betray the elements—and if wave-length 0·65 μ is absent, we say: Aha, hydrogen!—and if a black streak appears at 0·59 μ we know that there is sodium vapour in the Sun's atmosphere. In this way we find almost all the known elements—but never any others.

Absolutely never? Well, in 1890 Ramsay rediscovered a few particularly wide absorption-lines—they had long been known, but no one had been able to interpret them—in the Earth's atmosphere. This was the first clue, the first appearance of the stolen goods. From this to the detection of the thief was only a step—though the step was by no means an easy one. Ramsay found the culprit—a curious gas, which occurs in the Earth's atmosphere in very minute quantities, and was able to conceal itself so long because no chemical process has any hold over it. This gas will combine with no other element; it keeps itself to itself, a "noble" or "inert gas." Ramsay called it *helium* (Helios = the Sun). This was the element whose existence was first detected in the Sun—through its absorption-lines—and was now rediscovered in the atmosphere.

Babcock was even able to measure the "Zeeman effect" of

the lines of the solar spectrum. He found that in the black sunspots they were split up by magnetic fields—that one line might be turned into many—and he determined in this way the strength of the Sun's magnetic field. His source of light and his magnetic field were 93,000,000 miles distant. A laboratory in space!

The Quantum Theory

In this way the whole of the starry heavens has been spectroscopically examined. Always with the same results—we meet only old acquaintances. Just as the meteors, when they come rushing out of space, show always the same components—mainly nickel and iron—so the spectroscope shows without a doubt that the whole Universe is built of the same stuff—the ninety-two elements which we have found here on the Earth.

How great is our confidence in the uniformity of the Universe is proved by the famous example of the lines of the nebulae. In the stellar nebulae we found spectral lines of remarkable brilliance, which could not under any circumstances be related to a terrestrial element. Never would such lines be found on the Earth. It almost seemed as though there, in the grey, cloudy depths of space, a strange, mysterious element must be present—Nebulium, it was called—a real, original basic substance. Bowen, in America, solved the mystery. He found that the strange element was only nitrogen. The lines were nitrogen lines, which can never become visible under laboratory conditions—which for us appear to be "forbidden," because the atoms interfere with one another. Only in the remoteness of space, where hundreds of metres and kilometres divide atom from atom—only there can the nitrogen atoms find leisure to radiate the "forbidden lines" undisturbed! A laboratory in space! Many analogous lines—for example, a bright green light in the aurora—have been reproduced in the laboratory by means of certain devices. Some, like the green line in the Sun's corona, still constitute an unsolved problem. But no one doubts that one day these lines too will be ex-

plained—in a perfectly "natural" manner. That conditions and relations obtaining in space or in the Sun are unlike those of our laboratories will surprise no one. But the fundamental substance of the Universe is everywhere the same. Does not this seem to show that our knowledge is really reaching towards a frontier—that already we do really know something about the Universe? Never, it is obvious, will there be a lack of scientific problems; research can never attain its goal. But just as there was inevitably an end to our discoveries on the surface of the globe, just as the last blank patches disappeared from the map of the world, so our discoveries in the Universe will one day come to an end. No more elements will ever be found among the ninety-two—that at least is certain.—There is much evidence that in many different apartments of science we have reached such a limit. The science of the future will not be content with describing the facts as they offer themselves—it will have to put definite questions, conscious interrogations, to Nature; no longer expanding our knowledge, but making it more profound. It will be not a horizontal, but a vertical science.

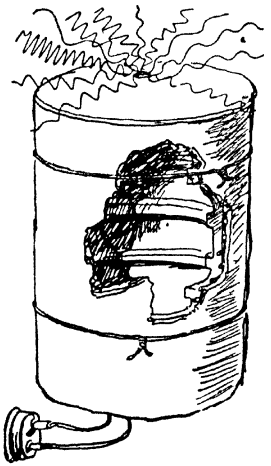
The spectroscopists have disappointed us. We wanted them to tell us how light originates. They have cleverly evaded the question, and have led us into the depths of space. The only clue they have given us is this: An undisturbed atom in an incandescent gas does not emit a band of light, but a series of sharply separated lines. Why this is so they cannot tell us.

Let us ask others; let us ask one of the great physicists, the German Nobel prizewinner, Geheimrat Planck, the creator of the quantum theory. "Listen, Your Excellency: whenever I have asked a modern physicist to tell me something of the origin of his latest theory, he invariably begins: 'Since Planck has recognized the existence of energy quanta. . . .' Now what does that mean?"

"Well," says the Geheimrat, "perhaps the simplest way of putting it is this: Radiant energy, the energy of the electromagnetic oscillations, consists, just as matter consists, of atoms. I have called the energy-atoms *quanta*: energy-quanta. And the problem from which I proceeded had long been recognized as of great theoretical interest: it was the

problem of radiation from an empty space, from a hollow container."

This hollow container is a sort of oven—a smooth, hollow cylinder, covered with asbestos packing. It is heated internally—for example, by an incandescent spiral. The heat-waves rush to and fro in the cylinder, until they are radiated into the outer world through a little hole in the cover. Waves of all possible lengths are wandering about in the cylinder, and are finally radiated—some strongly, some more faintly.



The distribution of the energy present in the wave-lengths was exactly measured, and it was necessary to find a theory which would explain the resulting curves. But it had to be recognized that the problem could not be solved by the methods of classic physics. So Planck found himself compelled to make this revolutionary assumption: The energy of these heat-waves, the radiant energy of these electromagnetic oscillations, consists of atoms.—It is an irony of fate that a classic and (in the best sense of the word) conservative thinker like Planck should have ushered in the new century with this revolutionary idea—that he should have been compelled, almost against his will, to enunciate the quantum theory! Ideas are often stronger than their progenitors!

We may ask whether this experiment constitutes an adequate reason for the acceptance of so heretical a theory. Naturally a single experiment, however important, cannot support or even justify a theory—or, for that matter, refute it. Experiments, unfortunately, are always negative witnesses, if we do obtain exact numerical values. They exclude this, that, and the other possibility; repeated, they exclude still more possibilities; in a moment they can annihilate the most attractive theories;

but they never of themselves give us positive information. They supply us always only with raw material—we have always to work upon their results, to construct a theory. So it may happen that a theory is not always in complete agreement with the experiments which it explains. There are even theories whose inherent probability is immediately apparent. Such was the quantum theory; and it subsequently justified the confidence with which it was received.

Energy consists of atoms. The hollow cylinder doesn't squirt out its energy like a hose-pipe—it throws it out bucketful by bucketful, just as a cook might constantly serve out the same quantity of soup with his great ladle. But there are larger and smaller ladles, of course, and also larger and smaller helpings. The energy-atoms are of various sizes—the higher the frequency of the electromagnetic waves, the larger the energy-atoms. You will remember that frequencies are measured in kilocycles, and that 1 kc. means a thousand oscillations per second. The "energy-quanta" of the waves 440 kc. are therefore twice as great as those of the waves 220 kc.; but each energy-quantum is in itself an indivisible unit—no more susceptible of division than an electron.

An inch measures 2·56 centimetres; so if I have a hundred inches of a new suiting I have 256 centimetres. If I have two hundred inches of cloth I have 512 centimetres. The number of centimetres increases in the same ratio as the number of inches, since the relation of inch to centimetre is always the same:

$$\frac{\text{Inch}}{\text{Centimetre}} = 2\cdot56$$

I said just now that the energy is greater in proportion as the number of oscillations is greater. If the frequency is

doubled so is the energy. Or we can say: The ratio of energy to frequency is always the same; or, writing it as a fraction:

$$\frac{\text{Energy}}{\text{Frequency}} \quad \text{constant}$$

But what number are we to substitute for the word "constant"?

We must ask Nature, by means of our experiments, what coefficient she has decided upon; and against her decision there is no appeal—though the factor may be infinitesimal. It is:

$$0{\cdot}000\ 000\ 000\ 000\ 000\ 000\ 000\ 000\ 006\ 55;$$

or, as the physicist and mathematician would write it: $6{\cdot}55 \times 10^{-27}$. That is indeed a small value; but it is important enough for physics. It has been given a name of its own; it is the "elementary quantum of action," and for convenience is denoted by "h." We can therefore write the equation thus:

$$\frac{\text{Energy E}}{\text{Frequency } v} = h: \quad \text{or, in shorter form, } \frac{\text{E}}{v} = h; \ \text{E} = h\,.\,v$$

where E stands for energy, and v for frequency. This amount of energy $h\,.\,v$ is thus the *quantum*—the smallest unit of energy, the energy-atom of the wave whose frequency is v.

Energy is doled out in quanta. This fact need not really surprise us. After all, these are quanta of electricity—the electrons. Nevertheless, the quanta of energy are by no means obliging entities. Perhaps this is because we have no possibility of forming any notion of energy. Of course, we cannot really form any conception of an atom or electron. But if it comes to that, we have always—let us be candid!—the extremely naïve idea of a tiny pellet; impossibly small, yet possibly visible, and at all events thinkable.

But energy we simply cannot imagine. What could it look like—whether heat, or gravity—and how are we to approach it? Here, for once in a way, we are honest enough, even in forming our concepts and images, to renounce any attempt

to imagine what energy is *like*. For all such attempts would be fruitless. And energy-quanta—energy-atoms! They are altogether too much for us. We can only resort to theory and experiment, and escape into mathematics, which with a few symbols, an equation $E = h \cdot v$, represents an energy quantum in a manner at once concise, intelligible, and exact. As an ordinary thing we are not aware of such crazy states of energy. And as in the case of the atoms, the fault is Nature's, for making the quanta so much too small.

A sewing-needle seems sharp, and a table-top smooth and level; yet under the microscope the one looks like a rugged tree-trunk and the other like a sort of Alpine landscape. Living creatures able to *see* the atoms would not find it necessary to speculate in order to acquire a notion of an atom. Beings able to *feel* the energy quanta would have an immediate impression of them, and would not have had to rely on Planck's flash of intuition. There are such beings—the electrons! But more of them later.

The frequencies of normal broadcasting waves run up to 1,500 kc./sec.—1,500,000 oscillations per second. A thousand billion billion of their quanta per second are equal to one watt. Twenty-five times as much energy will feed a small incandescent bulb. It may be imagined that we do not notice the individual effects of such "magnitudes" as the quanta. It is strange enough that they should produce any results of more than atomic importance.

The rest is easily guessed: Light also is an electromagnetic oscillation—so light also is ladled out in doses! There must be light-quanta!

This is quite a fresh clue in our hunt for the origin of light. And now at last we encounter the man who can tell us what we want to know. Niels Bohr of Copenhagen can explain the origin of light. Let us see how he does it.

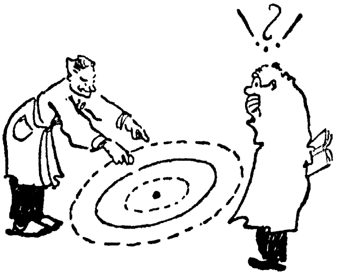
Hydrogen Ltd.

AN EPISODE

Persons:

Niels Bohr
An Electron
A Proton
Energy
Light
A Sceptical Physicist

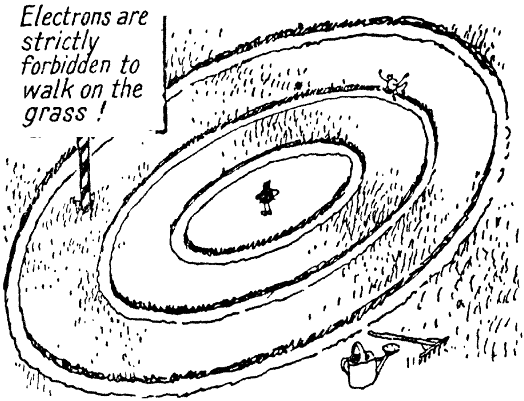
An electron was flying all alone in time and space, looking for a companion. Far in the distance, like a lighthouse in the darkness, twinkled a widowed proton. The two seemed made for each other, and it was easy to see what the end would be. Two lonely wanderers the less—one electron-proton marriage the more. The physicist thought, indeed, that he had come across a new hydrogen atom, for the electron that had found a home was travelling round the nucleus in a fine sweeping orbit. And from his standpoint he was right, but he was thinking in terms of physics, not of poetry.



Here Bohr takes a hand. You remember how Lord Rutherford built up the hydrogen-atom: A heavy proton in the middle, and the electron circling rapidly round it. Lord Rutherford was concerned only to see that positive and negative electricity balanced each other in his model; he had done nothing to fix the distance between the two; he only knew that this distance must be considerable. Bohr went farther. Strange as it sounds, he prescribed perfectly definite orbits for the electron. "Listen," he said: "I have found a number of orbits for you. Your distance from the nucleus can be 0·5 of a hundred-millionth part of a centimetre—but it can't in any case be less. This would be the first orbit, the one nearest the nucleus. The second has a radius of 2 hundred-millionths of a centimetre;

the third, of 4·5; the fourth of 8, and so on. Between the orbits, nothing!—In the same way a motorist, if he is tearing round the Ringstrassen of Vienna, is able to travel only on the five circuits—only where there are streets for him to drive on. He can't drive over the housetops and the courtyards."—You see, Bohr is the right man to deal with electrons. The electron acquiesced. It chose the second orbit.

But the sceptical physicist did not acquiesce.—"What's the



meaning of this? There are no housetops or courtyards in an atom! Yet you allow the electrons only a few widely separated orbits, at strictly prescribed intervals? How do you arrive at that?"

"That is my first postulate," Bohr replied. "I can't prove it, but it seems to me very reasonable."

"Well, well, but there's another question: This circling electron is in my jargon 'a moving electrical charge.' It has to radiate electrical energy. Maxwell's theory requires that it shall—and in practice the electromagnetic waves prove that it does! Well, then?"

"No," said Bohr firmly. "No, my electrons do not radiate! So long as they revolve in their lawful orbits they might as well be hidden away in a tunnel, as far as the outer world is

concerned. If Maxwell's theory isn't consistent with that, so much the worse for the theory!"

The sceptical philosopher was shocked into silence. This deliberate affront to the classic electrodynamics had wounded him deeply. How could he have any faith in Bohr after that?

In the meanwhile electron and proton were revolving round each other at the prescribed distance. Undoubtedly the pair represented something or other—a marriage, a purposeful association—"a physical system having a definite energy!" cried the physicist. But even an electron suffers from monotony after a time. "I should like to go round the third orbit," it said. —"Please do," replied Bohr.

"And the energy?" the sceptical philosopher interposed. "The energy, my dear sir! It's all very well to want a bigger orbit, but the system"—and he smiled a disdainful smile—"the system has too little energy! Think, Mr. Bohr—it takes work to drive the electron into the outer orbit—a step higher, so to speak. The pair hang together on their electrical attraction as though it were a length of elastic. I must have energy to stretch this catapult!"

"You shall have it," said Bohr consolingly. The justice of the demand persuaded him that it must be granted. "As to where it is to come from—leave that to me!" And he gave the electron a little energy, raised it a step higher, to the third orbit—and there it continued to revolve—for an eternity, or so it seemed to the electron. For electrons, it may be observed, have quite other notions of time than ours. A hundred-millionth of a second seemed quite long enough to this electron, and it knew this orbit now. And lo!—with a sudden jump, so that one really couldn't say how it happened, the electron sprang back into the second orbit.

It was really quite painful to see the sceptical physicist; he was carrying on like a madman. "What sort of behaviour is that?" he raved. "Unreliable, incalculable! What am I to do with the energy? Where is it—what is to happen to it? It evaporates, eh? Perhaps it flies off into the world like a bolt from a crossbow? Eh?"

"Perfectly correct. That is just what it does. The surplus energy—the same amount, I'll ask you to observe, which I

previously placed to the credit of the electron—flies out into the world again. The electron and proton are honest debtors —they pay in cash, in plain, round energy-quanta, what I advanced to them. For here they are revolving in their old orbit, with their old capital."

"Very good. Splendid!" said the physicist, with an ironical smile. "And how do you propose to prove this nonsensical theory? Perhaps I could see it, your famous energy-quantum, which flies off into space without so much as 'by your leave'?" —"Yes," said Bohr quietly. "You can see it!" And he waited in vain for a protest. The physicist stood with his mouth wide open. This impertinence was too much for him. But Niels Bohr took advantage of the pause and drew a pencil from his pocket. "I'll make out the invoice of Hydrogen Limited.

MESSRS. HYDROGEN LTD. (Electron & Proton)

Account rendered to

MR. NIELS BOHR, Copenhagen.

		e Volt
Carried over: Capital energy of 2nd Orbit (E_2)	..	10·15
Received from Mr. Bohr	..	1·88
Capital energy of 3rd Orbit (E_3)	*Total*	12·03
Expenses: 1 Light quantum for Mr. Bohr, 3 billionths of Erg ..	.. =	1·88
Energy of 2nd Orbit	..	10·15

"You see, the firm repaid me the advance of energy $E_3 - E_2 = 1 \cdot 88$ V. Of course, it paid me in different coin; it gave me an oscillation quantum $h \,.\, v$, electromagnetic, of 3 billionths of an erg. But 3 billionths of an erg are worth exactly $1 \cdot 88$ V; therefore we have the equation $E_3 - E_2 = h \,.\, v$, and we can now convert the quantum in accordance with the current rate of exchange. What price is h today?"

"You know as well as I do that h is invariable—it's $6 \cdot 55 \times 10^{-27}$ as always."

"Very well; then the oscillation-quantum repaid to me has

a wave-length of 0·65 μ. No one knows better than you what an oscillation of 0·65 μ means!"

"Light," said the physicist in astonishment. "Red light. The well-known hydrogen-line Hα. The identity-card of hydrogen!" —"Right!" replied Bohr, "Now do you believe that you can see energy? The firm Hydrogen Ltd. (E and P), are accustomed to paying their debts in light-energy. They repay credit given in the form of light. So the energy which in your opinion was lost goes out into the ether as a light-wave. I am always glad to deal with this firm. They are money-changers. Do you understand now? They don't hoard anything; they repay the whole of the energy which they borrowed of me in light-waves."

"Physically speaking, that is all in order," said the physicist; "and this energy-equation, $E_3 - E_2 = h \times v$? How do you get at that?"

"That is my second postulate," said Bohr, smiling vaguely.

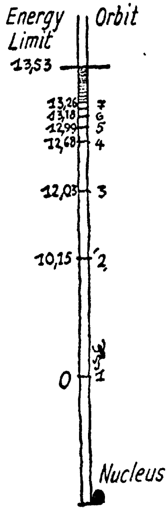
And that's how it is. The electrons of an atom are permitted to move only in definite orbits, with definite intervals between them, with definite amounts of energy; and they revolve in these orbits without radiating energy (Bohr's first postulate). But today we prefer to say: An atom can exist only in one of certain definite states of energy, which are divided by definite intervals.

Considering only the distance of the electron from the nucleus—and the distance alone determines the energy!—we may imagine the nucleus to be on the ground, and the electron on a certain higher plane. Rutherford said nothing definite about this; any height would have suited him. Bohr, however, defined the planes, like so many floors of a house, and said to the electron: "Choose any position you like—but, of course, you can only run about on the first, second, third, or *n*th floor. There's nothing between them." He insisted that there must be a series of stages for the electron, and also for the energy of the atom, whereas Rutherford would have consented to an inclined plane.

Our sketch shows the *energy-values* of the hydrogen orbits; as you will see, they grow closer and closer together as they become larger; that is, the difference of energy between any

two orbits becomes smaller and smaller. We must not confuse the energy with the *diameter* of the orbit, which rapidly increases; the second orbit is four times as large as the first, and the hundredth ten thousand times larger!

The orbit nearest the nucleus is the basic orbit. This is the orbit followed by the electron in its normal state; and at such times the atom has its minimum energy.



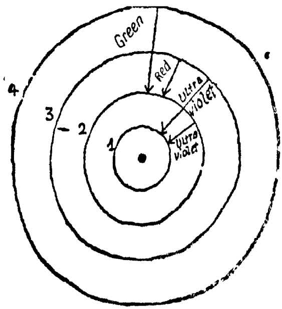
By the addition of energy from outside an electron is lifted to a higher orbit; the atom enters upon a state of greater energy—but only if the increment of energy is great enough to bridge over the energy-difference between the first and the second orbit. Smaller increments of energy are completely valueless. In this higher orbit the electron circles for a while—perhaps for a hundred-millionth of a second—then it returns of itself to a lower orbit, and radiates the energy thus released as an energy-quantum, as a light-wave, whose wave-length is of just such dimensions that the quantum contains the whole of the released energy.

$$\text{Initial energy minus final energy} = h \,.\, v$$
$$E_i - E_f = h \times v$$

This is Bohr's second postulate—for which the scientist never offered a shadow of proof. Success alone justified him; for on the basis of his two assumptions he was able to calculate theoretically the lines of hydrogen, and he obtained exactly the experimental values—within a fraction of a hundred-millionth of a centimetre; and we now understand why an atom gives a spectrum of luminous lines, and not a band of light. Every single line represents the transition from one state of energy to another.

Here is an example of this jumping process: Hydrogen radiates, in falling from the second orbit to the first, an ultra-violet line, and in falling from 3 to 1 a second line of even

shorter wave-length. Of course, the electron can also leap from the third orbit to the second. Then only part of the energy available is released—and we have the red hydrogen line Hα. Or it leaps from the fourth orbit to the second—and we obtain a fine green line Hβ, corresponding to the greater amount of energy released (shorter wave-length). Thus there are many possibilities—and one impossibility. Never can Hβ be radiated unless the electron was previously in the fourth orbit. This Franck and Hertz were able to prove by experiment.



Electrons are evaporated from an incandescent cathode, as in a radio valve, and accelerated by a positive grid potential—when they meet and collide with mercury atoms. Slowly the grid potential rises—one volt, two volts—but all is still dark in the field of the spectrograph. Three volts, four. . . . The velocity, the energy of the electrons is steadily rising, and the grid potential is approaching 4·9 volts, at which value, according to Bohr, the first energy-quanta should be delivered. At 4·9 volts—not a second earlier—the observer, gazing with almost painful attention into the darkness, cries "Stop!" Sharp and clear, the first bright green mercury lines appear in the field of vision—narrow and precise, a luminous signal. They appear instantaneously, without any transitional twilight. The energy-quanta have become visible. Electrons with the energy of 4·9 volts raise the atom to the second state of energy. The relapse follows automatically—and the energy, absorbed and then released, shows itself as *light*. The automatic mechanism is functioning. Only when the proper coin is dropped into it does it discharge the proper light-quanta in exchange. Smaller units of energy, smaller coins, are disdainfully returned—it has no use for them.

Step by step Franck and Hertz were able to determine the energy-stages of the atom; they read them directly in volts on their voltmeter. At 5·4 volts the third orbit was reached—

and at this moment precisely the second mercury-line appeared. The energy-quanta were *measured*—as surely as the seconds-hand of a watch measures units of time.

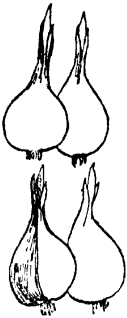
As a matter of fact, the experiment is usually carried out in a slightly different manner. The stream of electrons which passes through the tube is measured. Up to 4·9 volts it slowly rises—the electrons are tossed resiliently to and fro by the mercury-atoms, like so many billiard-balls, but they retain their velocity. They are even able to pass a slight counter-potential, a negatively charged grid. But at 4·9 the current suddenly falls to zero. The electrons with 4·9 volts of energy are using all their energy to stimulate the mercury-atoms—after which they are inert and motionless, and unable to overcome the counter-tension. At the same moment the green line appears. The greatest difficulty of this experiment, by reason of certain problems of pressure and screening, is to ensure the equable increase of potential. It is not so easy to make electrons travel at absolutely equal velocities. But Franck and Hertz, with their great technical skill, were able to overcome these difficulties.

So much for Bohr's explanation of the origin of light.

Bohr subsequently expanded his conceptions, thereby furnishing a wonderful and quite unforeseen explanation of the periodic system of the elements. He reduced the somewhat irregular horde of Rutherford's whirling electrons to order. He excogitated the onion-atom.—Proceeding outwards from the centre, the electrons are arranged in *shells*, which surround the nucleus at progressive intervals. The electrons revolve in their appointed orbits, but the two innermost only are inside the first shell; the six following electrons are inside the next shell, while the next after that contains ten electrons. And so on. Of course, the shells are not strictly delimited; electrons of the outer shell dive into the inner shells. The image is only approximately valid.

Each completely full shell is self-sufficient. It is sated, saturated; externally it is almost neutral, and is not very vulnerable to external influences. The elements which have the right number of electrons—whose shells are completely filled, without any gaps—will therefore, according to Bohr,

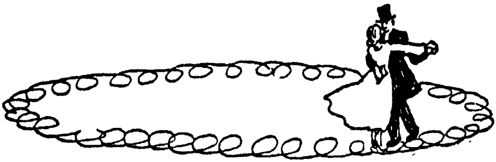
resemble one another—and they must be chemically lethargic, seldom or never uniting with other elements. Now, these elements are No. 2—helium; No. 8—neon; No. 18—argon. They are the "noble" or inert gases—and they are, as a matter of fact, chemically akin and absolutely inert. The "noble" gases form no compounds with other substances.—Bohr's onion-atom gives us an immediate explanation of the periodic system of the elements—of the fact that Rutherford, in building up his universe, was constantly encountering chemical relationships and similarities. An onion which has had one of its skins completely removed is at first sight indistinguishable from one that has been twice peeled—but is immediately distinguishable from one which has lost only half its first skin. And just as Mendeleieff was able to predict new elements with the aid of the first periodic system, so Bohr with his greater knowledge was able to provide even better indications. All the chemists had believed Element 72 to be a relation of the "rare earth metals"—a group of elements which are chemically closely related, and of which the best-known representative is Cer (cerium), which gives off the sparks in our cigarette-lighters; a group of elements which absolutely refused to fit into the old periodic system. Bohr not only explained this group—whose peculiarities were due to the supplementary formation of a deeply situated shell of electrons; he also saw that Element No. 72 could not belong to this group; that it contained no such supplementary inner shell, but was chemically related to zircon. A few months later Georg von Hevesy found Element 72 in zircon ores.



Niels Bohr's native city is Copenhagen; in Latin, Hafnia. The scientists have named the new element *hafnium*.

Spectroscopy, the science of light, had introduced into our notions of the atom a hitherto unknown order and consistency. It now went still farther—it made it necessary to endow the electrons with yet another new quality. Just as the Earth revolves round the Sun, and at the same time rotates on its own axis—just as a couple of dancers waltz round the ball-

room, and at the same time revolve upon themselves—so the electron, as it flashes round and round the nucleus, has also an individual movement of gyration—it spins upon its own axis. And it is evident that the energy of the atom would differ slightly, accordingly as the electron gyrated in the same direction as that of its path round the nucleus, or in the opposite direction, when the two movements of rotation would mutually conflict. Thus instead of one orbit we really have two, very close together—which explains why the well-known yellow sodium-line is double! Even a moderately good instrument shows two lines, close together. Their wave-lengths differ by six ten-millionths of a millimetre. Not a great difference, is it?



—but for the spectroscope it is enormous. Even the thousandth or ten-thousandth part of such a difference is plainly demonstrable. And recently the spectroscopists have been particularly interested in just these infinitesimal differences, and have found that neither of the two sodium lines is really a single line. Each of them is doubled again. (See Plate 3.)

The foundation of the atom is the nucleus. And we know of the nucleus also that it is not quiet and contented—that it also spins on its own axis—and so, by turning with or against the electrons, causes a fine subdivision of the lines of the spectrum. This superfine structure—as it is called—is investigated with apparatus which can distinguish differences of a few billionths of a centimetre. These investigations promise us further information concerning the nuclei of the atoms.

It may seem a matter of secondary importance that the electron and the nucleus should be possessed of "spin." Actually, it is a matter of the greatest importance—it is a primal quality of the elementary particles, as fundamentally important as their charge and mass. Each one of these particles,

whether electron, or proton, or neutron—even the light-quantum, the photon—spins incessantly upon its own axis. Dirac in England can tell us why. And we shall return to this presently.

The spectrum-band of an element with many electrons seems meaningless and bewildering. How are we to find order and significance in this oppressive multiplicity?—And yet the research-workers did find it—in a bare ten years most of the spectra have been thoroughly disentangled. We know the energy-stages of all the important atoms, and in many cases our knowledge is astonishingly exact. We know the orbits of the atoms and the leaps of the electrons—sometimes two electrons jump simultaneously!—which cause the bright lines of the spectrum; and all this has been determined with the aid of a remarkably simple theory and the recondite laws of wave-lengths, whose numerical relations almost verge upon the cabbalistic. We heard the music of the light, but we did not understand it. Niels Bohr has explained it for us.

Practice: The Mechanical Glow-worm

They were driving through the warm summer night from Hamburg to Berlin. The great car ate up the miles in silence, but for the faint crackle of the tyres on the concrete road. Yonder a fiery snake, the Berlin express, crept slowly through the darkness. Far ahead were the twinkling lights of a town or village, and an approaching car, the broad white rays of whose headlights seemed to push a section of the road before them —and heedlessly let it fall back into the darkness. "Like glow-worms," said the passenger, pointing ahead.

"Yes, like glow-worms," rejoined his friend at the steering-wheel, disdainfully. "Like glow-worms, the beastly things! They ought to be prohibited. But I'll show you my glow-worms presently! Just wait a bit!" The passenger said nothing, and stared in alarm at the dark, silent landscape. Could it be that his friend had gone absolutely crazy? Ought he to drive straight to a sanatorium? But a lighting engineer couldn't

really go crazy, he decided. Also, he wouldn't have expected such a thing of his friend.—"Perhaps you wouldn't mind . . ." But the other interrupted him. "It's really a scandal, the way people live. We are consuming our capital, consuming the last of our petroleum, our last tons of coal. They may last us some time yet, and we think—after us, the Deluge. But if that were only all! We are simply throwing energy out of the window with both hands. Steam-engines—20 per cent. Petrol motors, Diesel engines—30 per cent efficiency. And everybody enthuses over our technical progress if a mere two-thirds of the energy goes uselessly through the exhaust! And your beautiful lamps—I tell you, 12 per cent!

"And here you are talking about glow-worms. Yes, the glow-worms *are* efficient—we ought to hide our heads in shame!—No, one ought to smash them all!"

They drove on through the night.

"It's like this," the driver continued, in a quieter tone. "If I need a pair of braces or a collar-stud I walk into a shop, politely say 'Good morning,' choose my stud, put down my penny, and go. That's what a reasonable man does, isn't it? But there might be people who would go about it differently; they would send a few lorries to the warehouse and buy the whole stock. And in the end they'd find their collar-stud, among the woollen mufflers and concertinas. An efficient method, etc.? Well, it's often applied in technical processes. . . .

"Take the lighting engineers. They want to generate light—they want a wave-length between 0·4 and 0·66 μ. What do they do? They buy up the whole spectrum—between 100 μ and 0·2 μ; from the long-waved heat-rays to the short ultra-violet rays which nobody can see. Of course, there's visible light along with them. But Nature gives nothing for nothing; we have to pay for the heat-rays as well as for the visible light. That's the explanation of our amazing degree of efficiency. Twelve per cent of the energy we put in is really transformed into visible light. Twelve per cent at most. Not much better than a pinewood torch.

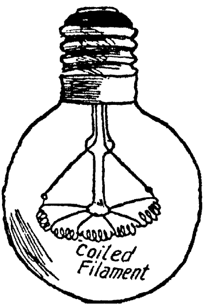
"But things can be done differently, and it's just that that gets my goat. The glow-worms are economical by temperament. They generate their cold green light by chemical means—and attain an incomparably higher degree of efficiency. An American physicist has measured it. Moreover, they don't just generate any sort of light; they have fixed on green, $0 \cdot 55\ \mu$—the wave-length to which human eyes, and probably the eyes of many animals, are particularly sensitive. But human beings have hardly got rid yet of the preconceived opinion that light can be generated only by fire, just like the men of the Stone Age, who sat in their caves by the flickering firelight."

"Of course," said the passenger. "Atavisms. Not so unusual in technical matters. But how can one do better? How does one make light?"

"That's just the point—until twenty years ago we simply didn't know how light does originate. Bohr was the first to show us. He elucidated the energy-exchanging mechanism of the atom, and Franck and Hertz have developed his theory.

"We light our lamps with 240 volts—but a few volts are quite enough, are more than enough energy. We have only got to offer them to the atom, the electron in the lamp, in an intelligent way. We heat an incandescent wire—that is, we make its atoms oscillate. The atoms, of course, are all elastically suspended; in their electrical fields, as though in a system of elastic threads. They sway gently to and fro; they have a certain temperature, a definite energy of oscillation—kinetic energy—according to the temperature of the room. We press the switch—and now a swarm of electrons flows through the wire, forcing itself through the gaps. The electrons jostle against the atoms, collide with them, increase their oscillatory movement, very much as a gust of wind—to use a rather crude analogy—sets the strings of an aeolian harp vibrating and sounding. And when the current increases, when the wind freshens, the atoms swing to and fro and more vigorously, oscillate more and more furiously—until finally, owing to their mutual disturbances, not only does the atomic assemblage oscillate as a whole, but even the individual electrons in the atoms begin to bestir themselves, until at last they begin to leap to and fro—up to a higher orbit and back again—until

finally they radiate light. They make a start with red light, which is long-waved and short of breath; it represents a low degree of energy. And if the current is increased the energy of oscillation increases; oscillations of higher and higher frequencies occur—yellow, white, bluish light at last. That's how it was with the old incandescent lamps. You know, they were exhausted of air so that conduction of heat might be avoided—so that the quivering atoms of the filament should not get rid of their energy by colliding with the surrounding air; unable to get rid of it, they had to oscillate all the more violently. An incandescent filament exposed to the open air could never become so hot, could never heat itself to such a degree, as in the exhausted bulb.



But these exhausted bulbs have one great disadvantage. Individual atoms tear themselves loose from the assembly—thanks to their energy of oscillation—evaporate from the filament, and fly across the bulb to the glass, where they settle down as a dark deposit. Gradually the whole filament decays in this fashion. Sooner or later it becomes too thin, and burns through, or fuses. The lamp is dead.

We shall have to find ways of delaying this evaporation. On a mountain-top water boils sooner than at sea-level—because of the lower atmospheric pressure. In mines and closed vessels it takes longer to boil—the high pressure on the water retards evaporation. We must increase the gaseous pressure in the lamp; then the filament can't disintegrate so rapidly. And at the same time we must reduce the conduction of heat to a minimum. This is effected by a simple device—we wind the filament into a spiral. Now only a fraction of the filament's length emits heat in an outward direction, for 10 inches of filament are wound into a spiral 1 inch in length. As far as the external environment is concerned, we have now a thick filament 1 inch long—so that the radiating surface has in this way been reduced to one-tenth. It now becomes possible to

fill the lamp with nitrogen or argon, and to heat the filament to a considerably higher temperature without making it evaporate. This is the principle of the gas-filled lamps—and with the new refractory alloys of wolfram and osmium we can get up to temperatures of 2,500° C. Compared with the old lamps, these bulbs are very efficient. They need only half a watt per candle-power; so a 25-watt lamp gives 50 candle-power. But the lamp still grows hot; even hotter. This is the wrong way to go about the business—the way to the warehouse.

"We ought to do as the glow-worm does. The glow-worm produces its light by chemical means. We can't do that, but even we might go to work in a reasonable fashion."

The car slowed down, and drove through the silent streets of a town. A few arc-lamps, hanging from cables that spanned the street, were swaying gently to and fro.—"The arc lamp too is on the wrong track. It too is a generator of heat. The current flows between the two carbon electrodes—through the air-gap, in which the air is at white heat, and therefore a conductor. And this current—a continual bombardment of electrons and ions—batters against the positive electrode, is there checked, and heats the carbon to a bright white heat. The temperature at the surface of the electrode may be as high as 4,000°; as you know, the highest fusing-points are reached by such an 'electric crucible.' The incandescent crater radiates the dazzling light. But here . . ." Here an electric sky-sign was doing its best to catch the eye: brilliant red, bright blue. Neon tubes, bent into the form of letters. "Have you ever taken hold of such a tube? You can do so without misgiving—the tubes are cold, quite cold. And that, do you see, is the right way.

"We have to make a gas, a vapour whose atoms are free to oscillate, radiate light without substantially increasing its temperature. We must bombard it with electrons—electrons are light!—and in this way excite the electrons of the individual atoms, lifting them to higher orbits and letting them fall back, without too greatly increasing the velocity of the atom, and consequently its temperature. And the thing is done!"

In the distance, above the horizon, was a strange glimmer of light. The travellers had left the little town far behind

them. "There they come—*my* glow-worms!" said the engineer, and it seemed to his companion that he could hear a secret triumph in his voice. Hanging across the street was a chain of shining moons, which threw a bright, curiously yellow light on the road-surface. "Sodium vapour! There's no filament in these lamps; they are filled with an atmosphere of sodium vapour, a dense swarm of sodium atoms. The electrons and ions which carry the current through the lamp collide with the sodium atoms, raising their electrons and letting them fall back, so that they send out a bright yellow light. This is the famous D-line. The principle is the same as that of the neon tubes. Here, at Döberitz on the Berlin to Hamburg road, is the first large-scale experiment with these lamps. That is *cold light*—the lamps don't grow hot—no thousand degrees there, no uselessly generated, uselessly squandered heat-energy. Here we have an efficiency of 30 per cent, and that, according to our present notions, is worth something."

The car raced over the brightly lit street towards its destination; it was nearing home.—"We shall catch up with the glow-worms yet," said the man at the steering-wheel.

Thinking Light

In Berlin there is an overhead railway-station on the Innsbrucker Platz. A travelling staircase, an escalator, leads to the overhead track. It is silent and motionless—until a passenger approaches. Then, suddenly, as though at the word of command, it begins to work, and carries the passenger up to the platform, where it immediately relapses into a state of unobtrusive rest—until another passenger appears. No secret switch, no double floor! Only a tiny beam of red light, an incorporeal barrier drawn across the passenger's path, from rail to rail, which he interrupts for a tenth of a second as he passes. This

brief cessation of the ray of light is enough to set the heavy electromotors working.

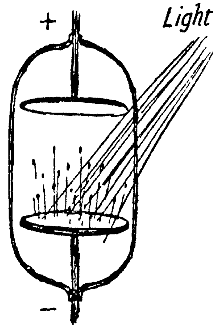
On an endless band the cigarettes glide away from the stamp that impresses the imprint of the firm, and onwards to the packing-machine. A narrow beam of light, past which they are led, feels them one by one. Then comes one which by some accident is lying with its imprint downwards, unlike the rest. The smooth, white paper reflects the light differently from the gilt lettering; immediately a lever reaches out and reverses the cigarette which has broken the ranks; now all will lie correctly in the box, with the imprint of the firm lying uppermost, as it should.

The show-window of the jeweller's shop is brightly lit, and undefended by a grille. But woe to him who attempts a "smash-and-grab" raid! An invisible grille of infra-red light, reflected to and fro, is outspread before the window—and the outstretched hand that interrupts the incorporeal filigree of rays will set an alarm-siren shrieking. The "thinking light-ray" will number the visitors to an exhibition. It will stop trains that have over-run the danger-signal; before long it will warn road-traffic of dangerous cross-roads.

On many "sound-films" you may occasionally see, on the left of the picture, a curious zigzag pattern rushing across the screen, like an irregularly toothed saw. This is the "sound" —music condensed upon celluloid. The light of the projection-apparatus is more or less diminished by the teeth; it falls on the "photo-cell," and after the current has been amplified many thousands of times the diaphragm of the loud-speaker oscillates in the same tempo—and we hear the voices or music. —There are exposure-meters for the use of photographers, which show the value of the light on a dial, just as an ammeter shows the strength of a current. They actually are ammeters; the exposure-meter contains an electric eye, a photo-cell. And the Americans, who are really so romantic at heart, made arrangements for the World Exposition at Chicago to be opened by a star—by light from space, which had left the star at the time of the first World Exposition at St. Louis, forty years previously. It passed through a refracting telescope and fell on a photo-cell, and this tiny gleam of light suddenly switched on

the lighting-circuit of the whole artificial city. The photo-cell —the eye of "thinking light"—is only a few years old—at least, in its application to engineering technique. Science has known of it for some decades. During the last few years it has become thoroughly naturalized.—But what is a photo-cell?

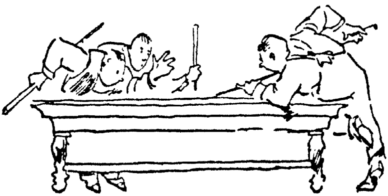
It is an incandescent lamp with a minus sign. By means of swiftly moving electrons we can generate light; make one kind of energy transform itself into another. The reverse of this process should also be possible—by means of light we should be able to generate movements in electrons.—It is possible. We allow light—a swarm of light-quanta—to fall upon a metallic film in space deprived of air—that is, an exhausted glass tube. Every light-quantum which falls upon the metal strikes an electron out of it, and this electron is carried off by an electric field by which the cell is surrounded. So long as light falls on the cell this current of "photo-electrons"—light-electrons—continues to flow. A stream of light has been transformed into a current of electricity. This cannot surprise us today; but it affords an admirable proof of our old assertion $E = h \cdot v$. For the greater the frequency, the shorter the waves of light, the greater is the velocity of the electrons—that is, their energy. However, not all the light-energy put into the cell is transferred to the electrons; a certain remnant, always the same, is lost. This remnant represents the work done in dragging the electrons into the open from the interior of the metal through the "electric skin," the surface-tension of the cathode. The shorter the light-waves, the greater the velocity of the electrons. The more light, the more electrons—the stronger the flood of light, the stronger the electrical "light-current." Theoretically all is as it should be. Every light-quantum liberates an electron—just as every electron, when it makes a jump, generates a light-quantum.



This is the photo-cell, the electric eye. Nowadays potassium or caesium cells, which are especially sensitive to red light,

and also to heat rays, are most commonly used. In these every variation of light, every change of intensity, as in the sound film or the cigarette machine, every interruption of the ray, as in the escalator, is converted into an equivalent pulse of current, the "photo-current," which is amplified by relays or amplifying valves until it is strong enough to be used for technical purposes.

The photo-cell is an excellent piece of evidence in support of the theory to which we have made so many references—the light-quantum hypothesis. Light, we are beginning to believe, does really consist, as Newtôn thought, of infinitesimal particles,



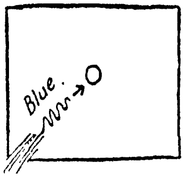
of light-atoms, "photons," light-quanta. However, for sceptics who refuse on principle to believe in any theory, we have in reserve another piece of direct evidence—the "Compton effect."

It is possible—as A. H. Compton was the first to show—to bombard free electrons with light. A free electron, when it comes into collision with a light-quantum, has no higher orbit at its disposal to which it can ascend; it has to consider how it can deal unaided with the impact and the consequent increment of energy. Accordingly, we shoot a light-quantum—using Röntgen-rays, so that the energy shall be great enough—at a free electron, which is moving only quite slowly in comparison with the velocity of the quantum.

In practice, what happens is very like what we may see on the billiard-table. A moving ball surrenders a little energy to a resting ball; and the two balls fly apart. So we may expect the following result: the electron and the light-quantum are thrown out of their paths by the impact. The new directions

must be such as can be calculated in accordance with the laws of elastic impacts. Impulse and energy are conserved, but part of the light energy is utilized in order to increase the velocity of the electron. Accordingly the Röntgen-ray loses energy; the quantum is a little redder, shifted a little farther towards the longer wave-lengths than before.

This is exactly what happens. We put in blue light and receive red light in return! Here we have this incredible phenomenon: a light-quantum that is able to change colour like a chameleon. The amount of light is, of course, very small, but it can easily be demonstrated. For the wave-theory this



phenomenon would have been yet one more enigma. The hypothesis of the light-quantum explains it with the greatest of ease: indeed, if there were no quantum theory as yet we should have to invent it in order to explain the Compton effect. We see that light has a twofold character; it shows two faces, Janus-like. For while we are obliged to speak of light-quanta, in order to explain the generation and destruction of light, there are other properties of light, such as the phenomena of refraction and interference, which are made intelligible only by the wave-hypothesis.

Voltaire came near to receiving absolution in his last moments. All his life long he was a convinced, cynically witty atheist. But on his death-bed the great freethinker suddenly sent for a priest.—Light is like Voltaire. It is born as a quantum, behaves all its life like a wave-motion—but dies as a quantum.

PART SIX

THE NEW IDEAS

I. THE ATOMIC THEORY

THIS, then, is the mystery, the missing first page of the story of light. We must admit that the case doesn't look very hopeful. Bohr has shown us how light is generated and destroyed; but he has not really explained it. He has applied a semi-classical method, with all its conceptual incompatibilities; guided, indeed, by an almost miraculous physical instinct, an intuitive certainty, which is all the more astonishing because it is manifestly opposed to the same classic laws which, on the other hand, are accepted as correct. This very commingling of methods calls for an incredible refinement of feeling for the physical content of the problem.

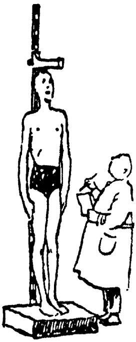
A story told of one of the great mathematicians of the nineteenth century—I think it was Gauss—has always impressed me, because it is characteristic of the co-operation of creative intuition, of the intuitive element, even in sciences so apparently intellectual and logical as mathematics and physics. He had discovered a wonderful mathematical principle—so he wrote to a friend—only he didn't, so far, quite see how it could be proved. But he hadn't the least doubt that his principle was correct!—We have a very similar case in Bohr's theory of the emission of light. Bohr discerned the nature of the generation of light correctly enough—indeed, with astonishing accuracy; the various energy-stages of the atoms; and the determination of the emitted frequency by the quantum-equation $E = h\nu$. But his "proof"—like the proof of Gauss's principle—was not quite conclusive. We know today that he interpreted his accurate perceptions incorrectly, and too intuitively.

In order to explain the different energy-states of an atom he was able to allot only certain orbits to the electrons; others were prohibited. Then he forbade the electrons to radiate in these orbits; they must remain in concealment, emitting no sign of their presence. Bohr could not explain to the electrons how they were to do this; yet, strangely enough, they seemed to obey him. And finally, he renewed Planck's old requirement in respect of the energy-quanta. Now, we are obliged to accept

this last requirement; the photo-cell and the Compton effect speak too plainly in its favour to be ignored.

The Victory of Whole Numbers

We will make a few concluding remarks in respect of Bohr's orbits. We are no longer surprised that the Earth should revolve round the Sun in a vast, far-flung ellipse. Here too we have a fixed orbit. Among many *conceivable* orbits it is the only one that has materialized. That a certain orbit has been selected—and selected in such a manner that it satisfies a mathematical formula—cannot constitute our chief intellectual difficulty. The formula, of course, is only a reflection of Nature, a symbol which represents our knowledge of Nature in mathematical language, as a photograph gives an image in light and shade. The Earth's orbit might have lain a hundred thousand miles nearer the Sun, or twenty miles farther out, if it had pleased the Creator. He chose one out of an infinite number of possibilities. It is otherwise with Bohr's orbits. They represent the *only* possibilities. Orbit one or orbit two—and nothing between. Need this surprise us?



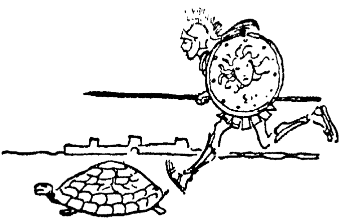
Our image of the world, naïvely considered, is coherent and continuous. But our measurements are all discrete. We say a man is 5 ft. 10½ in. in height. What that means, to be precise, is that his height is between 5 ft. 10 in. and 5 ft. 11 in. We are content to be accurate within a limit of half an inch—but if we insisted on giving his height within a thirty-second of an inch, or even a μ, it would still be an individual value.—A sprinter covers 100 metres in 10·4 seconds. Here we have the same case again. We are content with tenths of a second; the time can be measured to within a hundredth or a thousandth of a second, though this is seldom done.—Our currency is divided into shillings, pence, and farthings, dollars and cents; we don't go lower than this. We reckon in tons and hundredweights, or in grammes or grains if we want to be exact, and

the physicists even in milligrammes; but sooner or later we come to a limit. A cable may carry 20 amperes and 20,000 volts; or we can reckon in microvolts and milliamperes. But our practical world is always discrete, proceeding by leaps and bounds—by quanta; and this does not perturb us. Why should the thought of Bohr's orbits fill us with a certain discomfort?

The reason is plain—in all the examples given we ourselves have drawn the limit. In reckoning up sums of money it doesn't pay to go below a cent or a penny or a farthing; otherwise we could coin quarter-farthings, tenths of cents. A time measurement of adequate exactitude would give the result to a thousandth or a millionth part of a second instead of a tenth. We don't make such measurements because we don't need such exactitude. But we are always conscious of a *voluntary* limitation. In Bohr's theory, however, the discreteness is not imported into Nature by ourselves—it is there *in* Nature. Here lies the difference, and here is the origin of our intellectual discomfort. One of Nature's limits has been reached. We are brought up short by the notion of *number*. We count 1, 2, 3 . . . and here the notion of discreteness lies hidden. From 1 to 2 is a perfectly arbitrary and almost insuperable antithesis. The natural numbers are mobile points hovering in space. And now our apprehensive dislike of the jump begins to operate. We throw bridges from one point to another, connecting them by a straight line, and fill the empty space with a closer and closer palisade of fractions—1·1, 1·2, 1·3, 1·4 —and finally we think we have built a sufficiently firm and solid causeway, across which we strut proudly to and fro—and we think we have thereby conquered the dark, empty space. Yet our timid glance is constantly piercing the joints of our structure, and perceiving, with a strange thrill of dread, the nothingness beyond.

No, we have not conquered it; our hope was deceptive. This last, impassable bit of nothingness has a mysterious power of attraction—we feel that here and nowhere else is the secret of continuous space—here the mystery of the "continuum" begins. Space cannot be grasped by means of co-ordinates and figures. It penetrates them, submerges them, as water penetrates and submerges the close mesh of a sieve.

Here and nowhere else must the transition to time be found—time, which runs equably and uninterruptedly—"continuous" also in its own fashion. The Greeks were familiar with the problem—the Eleatic school of philosophers covered the ticklish spot of our intellect with an ingenious paradox. Achilles and the tortoise ran their famous race, the tortoise being given 100 yards start. When Achilles, thanks to his ten times greater speed, had run the 100 yards, the tortoise was 10 yards ahead. He ran this distance of 10 yards—and the tortoise was only 1 yard in front of him. He ran this yard—the tortoise was a tenth of a yard in advance. He ran the tenth of a yard—



the tortoise was a hundredth of a yard ahead of him—and so on. Let the runner strain as he will, he must always come to a place which the tortoise has just left, so he can never overtake it!—The case is clear—it could not be made clearer: space cannot be exhaustively described by measured lengths, by numerical statements. The Greeks never attempted to resolve this contradiction. It is said that the Greeks had static, and that we have dynamic minds. Perhaps it is so. At all events, nearly two thousand years had to pass, and a new mode of thought had to be created, before this contradiction was resolved.

This new mode was the new mathematical language—the differential calculus, which Newton and Leibniz had to invent, in order to comprehend the problem of movement in space and time. A mathematical mode of thought which, when all is said, jumps with one bold leap over the dangerous place, the boundary between the point and nothing. A mode of thought which bridles infinity and treats the infinitely small as a normal magnitude. It ignores danger—and thereby overcomes it. Since Newton's day the laws of Nature have been expressed as differential equations. Equations which include time. Equations which are continuous. In short, continuous functions. For two hundred and fifty years of traditional

thinking the scientists have laboured at such equations. A differential equation contains the notion of change. If I know the position of the Earth and the Sun on Monday, it is possible to calculate them for Tuesday and Wednesday, and indeed for any future point of time. The typical example of the potentialities of mathematics is furnished by astronomy, which calculates the data of new planets from the orbital deviations of the old ones, although in this case the differential equation cannot be so exactly solved. But the approximate solution is sufficiently exact.

It is only logical that from the nineteenth century onwards the concept of the field should progressively assert itself, and that Huygens's wave-theory, for example, should displace Newton's corpuscular theory of light. Even the notion of an electrical field, for instance, which fills the whole of space without a gap, and represents only a condition of space, is perfectly in harmony with the character of the differential equation. The continuum is thereby mathematically tamed and comprehended. And even though the intellectual difficulty of which I have spoken is not eliminated, even though space cannot be exhausted with a system of co-ordinates, even though numbers fail us, yet this difficulty no longer seems so important. Speaking crudely, numbers are not natural. Nature, it seems to us, is continuous. Her best-fitting mathematical dress is the fluent differential equation—Newton gave it the peculiar name of fluxional equation!—and the rigid scaffolding of numbers is merely a strait-jacket, the creation of the primitive human intellect.

But of recent years a great counter-offensive has begun from the other side, the side of numbers. They mustered in their myriads; tiny, invisible, but insuperable: the atoms. An atom used to be something final, something unique and indivisible—a *unit*. The notion of the atom enabled number to survive into the new age. Space remained continuous and fluent. Matter became a sort of patchwork. It no longer filled space—it was a fragmentary structure founded upon space. That Rutherford subsequently succeeded in splitting the atom, that protons and electrons have taken over the rôle of the final units, is a change of secondary importance. But it is of impor-

tance that the atom is not a differential—it only *moves* in accordance with differential equations. On this we insist. A falling atom complies with Newton's equations, just as do the Sun and the Earth. But the atom and the notion of the field are not compatible. The atom cannot, like the field, be *represented by a differential equation.* The concepts do not coincide.

Now, according to Bohr's assumptions, the corrosive malady went even farther. And the overwhelming thing about Bohr's notion was simply this—that even space, *the primal type of the continuous, was, in a certain sense, given an atomic structure.* Space, said Kant, is everywhere equal and possessed of equal powers. It is no longer so in the interior of an atom. Certain definite orbits are described, are possible—others are unthinkable. As though, in empty nothingness, beaten tracks, special paths were prepared for the electrons, in which they could run free and unhindered—as though the space beside them were uneven and bristling with briars, offering no thoroughfare. Was it any wonder that Bohr's theory met with the most violent opposition, that it was hardly taken seriously?

Indeterminacy

All this, perhaps, might have been overlooked for a time, but it gradually became apparent that Bohr's theory was not sufficient. It explained many things imperfectly, and some not at all, while some of its conclusions were even erroneous. On the other hand, its successes were great and indisputable; and it must, at all events, have contained a great many correct ideas. And here we are reminded of a similar case of a supplementary claim. In the early days of the theory of relativity came the unsuccessful Michelson experiment. Lorentz and Fitzgerald were able to explain it by the "irrational" requirement of the Lorentz contraction. And behold, this impossible claim by which Nature contrived, with the greatest cunning, to conceal any state of motion against the ether, actually contained the truth. But it became intelligible only when considered from the universal standpoint of Einstein, who made a clean sweep of "absolute" simultaneousness, relegating it to the region of the physically undemonstrable. We must arm our-

selves with the same sceptical caution, and go hunting for the inadmissible concepts which, in despite of all precautions, may still be lurking concealed in the structure of physics. We shall then reject them, and we may hope that in this way we may come to an understanding of Bohr's requirements.

LOCUS IMPULSE

I want you to solve a simple problem: Here, on the left side of the page, is the word "Locus." Let us look at it closely! On the right is the word "Impulse." Can you read it plainly? And now look at both these words simultaneously! Try to see them both plainly and distinctly at one and the same time. Can you? I confess I can't. I can see the word "Locus" distinctly, but then "Impulse" is a blurred and shadowy something to the right of my field of vision; or I fix my eyes upon "Impulse," and then I can no longer read "Locus." Or I look about midway between them—and perhaps this is best; then I see both words, but rather indistinctly. And since I am a physicist I do not hesitate to formulate the axiom: Locus and Impulse cannot be definitely ascertained simultaneously.

And here I have discovered the basis of the new quantum mechanics, the famous indeterminacy-principle of Werner Heisenberg, the Nobel prizewinner.

Now, this is mere fooling, and I am afraid Professor Heisenberg would be indignant if he heard me. But the doctrine is correct; and now we will consider the argument of Heisenberg's famous intellectual experiment.

Suppose we did not believe Niels Bohr, and wanted to test his theory. Suppose we wanted to convince ourselves with our own eyes that the hurrying electrons do really jump and revolve as Bohr says. We should want to determine their orbits, their position, their velocity, and their impulse (remembering that mass $\times$ velocity was defined as impulse). There is only one way of doing this—namely, to watch them. We are offered a microscope. But an optical microscope won't be enough; we know that the microscope is able to show us only objects of at least the dimensions of a wave-length. We must go to work

with short-wave light. Even ultra-violet rays will not be nearly short enough. Röntgen-rays?—well, with them one could just see the atom as a whole. We decide upon the gamma rays, which are even shorter than the X-rays. The microscope is ready for use. (Its internal construction is still a trade secret, but we needn't bother about that.) We look through it and see a point flash out—the electron! Then—nothing.

Why has it suddenly disappeared from the field of vision—just as the matter was beginning to be interesting, and we had caught a glimpse of the orbit?—The light-quantum with which we illuminated the field, the gamma-quantum, caused the most terrible disorder when it encountered the electron, for it simply flung it out of its orbit. We saw by the one flash of light where the electron was, but we can no longer say precisely where it went, or how quickly. *Our observation, our measurement, disturbed the course of the atomic process.*

This is the plain fact: Always, however we devise the experiment, our measurement will cause a disturbance. The observer and the atom are coupled together by the measuring-instrument. And this instrument is not merely imaginary—it is a physical reality. The processes occurring in it must have a perturbing effect upon the atom. It is absolutely, fundamentally impossible to observe, in the ordinary sense of the word, anything smaller than an atom. We have not obtained complete knowledge of an electron because at a given moment we were able to determine its place. We want to know its velocity also, for we want to be able to specify where it will be next moment. But measurement gives us only the place, the point of light; it does not tell us the velocity. It might occur to us to make the observation with the aid of less inconsiderate and longer waves of light. Then the electron will not be thrown out of its orbit—but we shall no longer see it distinctly. And so it is always. We want to determine two properties of the electron, which are mutually related; but we cannot by any method obtain both at once. It was Heisenberg who first clearly recognized this fact; he was able even to express it numerically. We have to reckon with a certain error in both values, and the product of the two errors cannot, in theory, be reduced below a certain figure. But the amount of the inevitable error is given to us by the

inexorable and ubiquitous Planck's constant h, the elementary force-quantum.

h is small. In the macroscopic world the problem disappears. A racing car overshoots the goal; I measure it correctly to within a thousandth part of a millimetre, which will surely be accurate enough! Now I measure its speed—which is, for example, 265·577 kilometres per hour. I could get a better timing-clock and try to measure the speed more accurately. Heisenberg's indeterminacy-principle sets a limit to measurement only at the thirtieth place after the decimal point—at one-quintillionth part of a kilometre. So the racing motorist's demand for accuracy can easily be satisfied. It is only in atomic measurements that indeterminacy plays a part, and there it becomes tyrannical.

An atom measures about one hundred-millionth of a centimetre in diameter; so that the position of an electron must be ascertained to within about one thousand-millionth of a centimetre. Now we try to measure the velocity of the electron. The Heisenberg-principle smiles derisively, and says: Do it by all means, but you mustn't object to an error of 60,000 kilometres per second in your result!—Well, that is not a very good measurement.

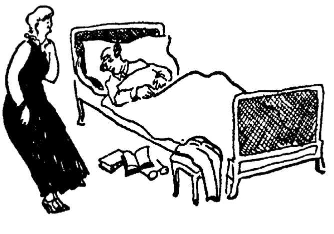
And Heisenberg goes a step farther: he denies the reality of what cannot on principle be seen. He denies that we have any right to form a visual conception of the atom. Here we have the unreliable intellectual hypothesis for which we were looking. We have simply transported concepts which have a plain signification in daily life, such as place and velocity, into the interior of the atom. We tacitly assume in advance that we shall be able to make measurements there. This was an error. Just as it was meaningless to apply the notion of temperature to a single molecule (p. 62), so it is meaningless to speak of the orbit of an electron. What we can observe in the atom are the lines of its spectrum, their intensity and their polarization. These, then, are physical realities. For convenience of calculation, I can make a model representation of an atom, just as I could make a simplified, schematic sketch of a radio receiver. Bohr's atomic model was such a representation. Whether this model corresponds in all its features to the reality is another

question. Or, to be more precise, it is not a question at all. We mustn't try to arrive at the reality by such means. The lines of the spectrum are real.

On these and these alone—on the wave-length and intensity of the lines of the spectrum—Heisenberg founded his new mechanics, his "matrix mechanics." He replaces the atom by a "matrix," a sort of table on which the lines of the spectrum are described. Concepts like "electronic orbits" have radically disappeared—the new theory is cold and abstract, and has resolutely renounced any attempt at objectification. But it most convincingly confirms the observed experimental data, and has been unexpectedly fertile of results for the whole science of physics.

Causality

The story was told of a famous and absent-minded professor that he had invited some guests to his house, but he himself came home late, with his dress in extreme disorder. His wife met him at the front door and, horrified by his appearance, sent him straight to his bedroom: he must at least put on a clean collar. He disappeared. A quarter of an hour passed; half an hour; his wife became uneasy. What was he up to now? Full of misgivings, she hurried off to his bedroom—and there lay the professor in bed, peacefully sleeping.



This, you see, we should call a causal consequence. The professor had taken off his collar—and as a matter of habit the shirt followed the collar, and so forth, until he crept into bed and switched off the light, as he did every evening. The professor slept—a victim of the principle of causality.

I press my foot on the brake-pedal of a motor-car: It pulls up. This is a causal effect, a causative connexion. The car will never—provided it is in order, of course—begin to go

faster instead of pulling up when I press the brake-pedal. A given procedure causes always the same effect, external circumstances being equal; it won't produce one effect today and another tomorrow. Once I have made the experiment, I can prophesy with absolute certainty: If the car is in order, and I press the brake-pedal, it will pull up.

In the whole of physics we are concerned with discovering such connections. I pick up a stone and let it fall. Since I know the laws of falling bodies, I can predict with absolute certainty: The stone will fall, and with such or such a velocity. The time of fall and the velocity of fall can be exactly calculated. The classic physics tells me: If I have exact knowledge of the state of the stone at a given moment, I can forthwith predict its future behaviour. But what if I take an electron instead? We must ask Heisenberg—since his indeterminacy-principle holds good for atoms and electrons. But Heisenberg shakes his head. We must have exact knowledge of the state of the electron—locus and velocity—and this, as we have seen, is impossible. And if it is axiomatically impossible that we should ever possess the necessary information, then we cannot say what it will do in the next second. No one can say exactly. The electron always keeps the last, decisive part of its secret to itself; it always remains to a certain extent incalculable. But do we know that the electron itself is any better informed? According to Heisenberg's way of thinking, the question is inadmissible. If we can never know exactly what an electron will do, it actually *is* quite uncertain what it will do. It can do this; it can also, within the limits of the indeterminacy-principle do something else. Heisenberg says: "In the sentence: 'If we have exact knowledge of the present in all its parts, we can exactly predict the future,' it is not the conclusion, but the preliminary assumption that is false. Axiomatically, we cannot have exact knowledge of the present."

Quantum mechanics persisted for a long time in maintaining that it had abolished the notion of causality. The philosophers assumed the offensive, and declared that the contentions of the physicists were erroneous and invalid. But it seems as though the physicists and philosophers, in their embittered conflict, were talking at cross-purposes most of the time. Causality, it

seems to us, signifies a mode of thought which we cannot surrender unless we are willing to turn our backs on science itself. But I do not believe that the professors of quantum-mechanics would really do this. Their realm is physics—and physics alone. Incidental and unqualified raids into alien territory may justly be repulsed by the philosophers. Moreover, even quantum mechanics does not assert that henceforth everything is to be regarded as due to blind chance.

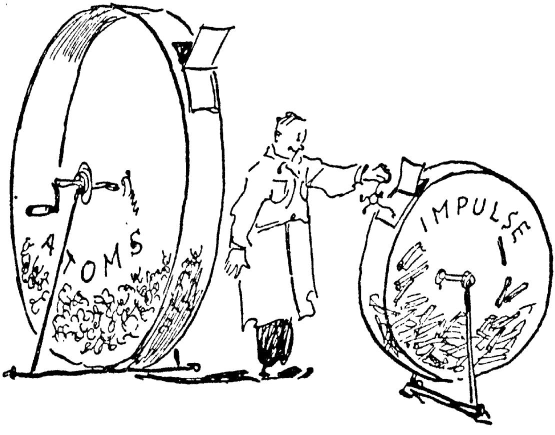
Its method is statistical. Suppose I have a number of atoms in a box, and make them "as like one another as possible"—do my best to reduce them all to the same state. The classic physics would have cancelled this phrase—"do my best to reduce them." Axiomatically, at all events, it cannot see that there could be the least difficulty in reducing a number of atoms to exactly the same state. Quantum mechanics is much more modest—of necessity. It has to grant that owing to the indeterminacy-principle states which are only very slightly different from one another can no longer be distinguished, and therefore regards them as similar.

And now Heisenberg puts the atoms into a lottery. He takes them out of their box, one after the other, and subjects them to a measurement—investigates, for example, the amount of their impulse. It cannot be expected that measurement will allot the same impulse to every atom. The initial state of affairs was much too indeterminate for this to be possible. Now, Heisenberg has made ready a whole heap of impulse-values—they are the prizes in the draw. There are big, little, and middling values—valuable and trivial prizes. But Heisenberg does not know whether the ten-pound or the five-pound prizes in his drum are the more numerous. That he will learn from the lottery.

The atom reaches into the prize drum and chooses an impulse-value. But we must bear this in mind: Before the draw it doesn't know what value it is going to receive. Before measurement the atom is in a "state of indeterminate impulse." Only when it is measured, when it reaches into the drum, does it decide for a definite impulse-value. Atom after atom draws its prize; there are no blanks in this lottery! And now Heisenberg compares the prizes drawn, and he finds that the ten-

pound prizes are the most numerous; then, perhaps, the five-pound prizes, etc. Now he knows what he wanted to know —how frequently each prize, each impulse-value, occurred in the drum. He has worked out the prize scheme of his lottery —he can now assert how great is the probability, on measurement, of receiving a given impulse-value.

At State lotteries the prize scheme is seldom altered. In Heisenberg's atomic lottery this is done continually. Let us



reflect that the prize scheme depends on the state of the atoms. The state of the atoms decides which impulse-value is drawn most frequently—that is, which was most frequently present. But the state of the atoms varies in the course of time—otherwise there would be no physical problem. If the atoms were always the same what would there be to investigate? Variety is life.

The state of the atoms will gradually undergo change, and now a second draw will give a different result; for now another impulse-value will be drawn most frequently. But quantum mechanics allows us to calculate exactly and unequivocally all the prize-schemes which may in the course of time evolve out of the first.

The method by which this is done is the "matrix mechanics"

of Heisenberg, and it is in this form that the law of causality is now expressed. The statistics of the atoms have been drawn up, and the probabilities of the individual values determined. Now it is possible to calculate, exactly and for all future time, how this probability will alter in the course of time. Only—I should think myself unreasonable if I expected more of the future than of the present. For the future I can draw up only one statistic—the probability with which each individual value will emerge. But quantum mechanics permits me to calculate the second probability *exactly* from the first.

Waves of Matter

There is yet a second way of attacking the problem of atomic mechanics: "wave mechanics." It seems to be the very antithesis of Heisenberg's mechanics. But its mathematical content is the same, and today it is only mathematics that matters. It received its experimental baptism from the celebrated experiment of Davisson and Germer. You remember von Laue and the black spots on his diagrams? We know how he sent Röntgen-rays through a crystal, obtaining, in this system of "interference-points" a picture, a symbol of the trellis-work structure of the crystal; proving thereby that the Röntgen-rays are a wave-motion. Wherever interference figures are observed there must be wave-crests and wave-troughs, which can reinforce or cancel each other. Laue's method was a triumph of the classic physics and its concepts.—This was in the year 1912.

Fifteen years later, in 1927, the classic physics was finally done to death by just the same method. Davisson and Germer, two Americans, repeated Laue's experiment with—electricity.

They sent a beam of electrons—that is, a swarm of swiftly moving electrons—all flying in the same direction, and with the same velocity, through a crystal. What happens in such a case?

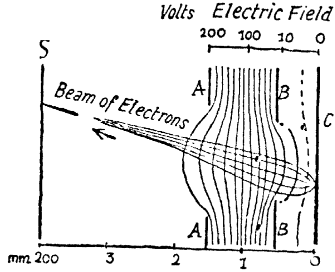
You may have seen something of this sort in a country fair or an amusement park: A ball falls through a regular maze of pins, bouncing now to the right, now to the left, and so reeling downwards in a zigzag line. At the bottom of the maze you try to catch it in a movable funnel—sometimes shaped like

a clown with his conical hat reversed. But as the ball is diverted in a quite irregular and fortuitous manner, the player does not often catch it, and his penny is lost.—The ball falls in an irregular and fortuitous manner. The classic physicists would have expected the electrons to do the same—they would be quite fortuitously diverted in their passage through the crystal as they flew past the atoms of the crystal, bouncing now to the right, now to the left.—After they have passed through the crystal the electrons can be caught on a photographic plate. (Electrons have the power of blackening the plate.) The classic physicist does a little calculation, and then says: One will get a rather washy, blurred patch of such-and-such dimensions; the ray will be a little scattered. But Davisson and Germer obtained something very different; they obtained the clear-cut system of Laue interference-points! (see Plate 4). *The electrons produce the same interference phenomenon as the Röntgen-rays. They are a wave process, a "matter wave." The wave-length is approximately equal to that of the Röntgen-rays.* The evidence is plain enough.

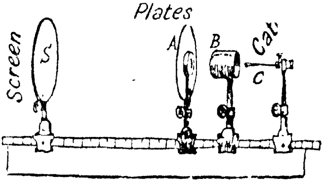
Does this seem absurd? Perhaps we ought to be able to *see* electricity when it is a wave? Well, we can; much as we can look into the human body with the help of Röntgen-rays. The famous Röntgen microscope, of which the physicists had long been dreaming, ought to make it possible to see details ten thousand times smaller than an ordinary microscope (since the wave-length of the Röntgen-rays is about ten thousand times smaller than that of light). If—yes, if we could make lenses for Röntgen-rays! But we cannot: Röntgen-rays are not refracted by any sort of lens.

But the "matter wave" of an electron is of the same order of magnitude as the Röntgen waves—and we can make lenses for electrons. Suitable electric or magnetic fields will divert a beam of electrons: You will see, in the sketch, how the lines

of the electric field swell out of the hole in the condenser-plates and assume externally a perfect lenticular form. A pencil of electrons, radiated by an incandescent cathode, is concentrated into a point—just like a light-ray on passing through a lens—and so an "electron-image" of the cathode is formed. In the plane of the image a fluorescent screen is placed, which lights up to a bright green where the electrons fall upon it. In this way the electron-image is translated into visibility—as in a bootmaker's shop an X-ray image of the bones of the feet is made visible by a fluorescent screen. And this picture reveals—or will do so when the necessary technical improvements have been made—details ten thousand times as fine as those revealed by the microscope. The theoretical resolving power is at one stroke increased ten-thousandfold.



We have not as yet obtained such magnifications. But another possibility is even more important. By means of the electron-microscope Brücke and Johannson have succeeded in making visible the electrical processes in the incandescent cathode, the emission of electrons. In this way they have made absolutely new and technically important discoveries concerning the process of emission (Plate 5). And they tell us: "Perhaps one day we shall be able to build electronic telescopes—then we shall be able to observe a distant, electron-emitting world. Perhaps we shall see the sunspots with their electrical craters and the eruptive processes of the electric particle!"



Component Parts of the Electronic Microscope

The complaint is often made that the new theory is no longer

in touch with reality. Matter, in the hands of new and utterly reckless men, has taken flight; nothing is left, after the ruthless overthrow of the good old classic physics, but a few mysterious, lifeless mathematical symbols. But this reproach can hardly be justified when the theory is able to find support in such tangible evidence as the Davisson experiment and the electron microscope. It is the old story: we can't order Nature to be what we should like her to be; we have to accept her. We must surrender a series of untenable, unjustified intellectual hypotheses.

But before all else we must approach such (I confess) rather intimidating expressions as "matter-waves," "interference of probability," with the necessary lack of prejudice. Then the spectres will lose their alarming aspect and become quite reasonable.

You take exception to the expression "matter-waves"? Then you must blame Hittorf and Crookes, who made their discovery of the electron too soon. Let us imagine that they never existed; let us assume that no one ever had any notion of electrons and protons, or Rutherford's "nucleus-atom," and so forth; let us suppose that we know only one thing: There is such a thing as electricity, which under certain circumstances can travel freely in space as a "cathode-ray." The cathode-ray is sent through a nickel crystal, and it is observed that interference occurs. "Very good," the observer says, and he writes to the scientific Press: "I have shown by my crystal experiment that electricity and the cathode-rays are a wave-process." Von Laue, Young, and Fresnel had no more to go upon.

It may seem a kind of accident that we did not recognize the wave-character of matter at a much earlier date. But Heisenberg's arguments have shown that the strange, equivocal behaviour of Nature, which we are trying to comprehend by means of the new forms of quantum and wave-mechanics, begins in atomic dimensions—in the sub-Lilliputian world which was reserved for the physics of the twentieth century.

It says much for the theorists that they did not wait for the Davisson experiment, but had endeavoured to embrace the disconcerting idea of "matter-waves" some years earlier Prince Louis de Broglie was the first to do so, in 1923.

Then, perhaps for the first time in the history of physics, the investigators lost confidence. Always, previously, so long as physical research had been undertaken, it had been regarded as self-evident that Nature must behave "rationally"; that she would avoid contradictions, and even—and this is assuming a good deal!—that it must be possible to *visualize* or *objectify* her processes; that it would always be possible to form a homogeneous picture of all natural phenomena. But this is just what many are beginning to doubt today.

Amphibia

The physicists of the twentieth century were surprised by the disobliging behaviour of light.

Hitherto physics had not reckoned with amphibious things, with beings equally at home on land or in the water. But now it was admitted that light refused to fit itself into any simple scheme—it was wave and quantum at once. Light was an amphibian. The next thing to do was to inquire whether perhaps matter, hitherto regarded as innocent and earth-bound, whether electrons and protons, could also swim! Whether they too were amphibia—whether they too had the character of waves!

The first step in this direction was made a long while ago. Sir William Hamilton, more than a hundred years ago, succeeded in subordinating mechanics to a universal principle, which bears a startling similarity to the principle of the "hurrying light-ray." The mathematical form of both principles is precisely the same; and as a matter of fact Hamilton himself had worked towards a unification of mechanical and optical principles. But at that time not enough was known. His age was not yet ripe for the final synthesis; yet Hamilton, with the certainty of a somnambulist, had done the preliminary mathematical spade-work. Later on it was this, the very nucleus of his work, that was forgotten, and the principle of continuity which he discovered was reckoned a mathematical curiosity, no more.

A light-ray, you will remember, always travels in such a path that it reaches its goal as quickly as possible. This principle

is made comprehensible only by the wave-theory: the curving of the light-rays in the atmosphere, for example, is a consequence of the gradual wheeling inwards of the wave-fronts (p. 143). A stone, thrown from the hand, in the gravitational field of the Earth, or an electron in a field of electrical forces, follows a curved path. This path can be deduced from Hamilton's principle.

And Schrödinger says: It cannot be accident that the two principles are mathematically so similar. Such accidents do not occur. I must interpret the Hamiltonian principle in terms of waves if I wish to understand it. Then it becomes as self-evident as the principle of the hurrying light-ray—then both principles coincide. I must try to co-ordinate the stone and the electron with a wave-motion. But how is that to be done?

Let us recall the quantum formula:

$$\text{Energy} = h \times \text{frequency}$$
$$\mathrm{E} = h \times v$$

In this shape the formula refers to light: The wave of frequency v corresponds to energy E.

Or we say, in a "material" sense:

To the electron with energy E corresponds a wave of frequency v.

The Davisson experiment is the tangible evidence for the second way of reading the equation. You see: light and matter can be read into the same equation in different directions. Both light and matter are amphibious by nature. For both of them the decision: Either wave or particle (corpuscle) is impossible. It is a case of "both wave and particle."

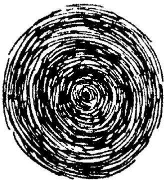
To calculate the wave-length of an electron we must express its energy in the equation, and in so doing we must allow for its "energy of mass," in accordance with the theory of relativity (p. 207). As we have said, the "matter-wave" of an ordinary electron measures a few hundred-millionths of a centimetre. Of course, you are justified also in interpreting yourself as a wave-process, and then your corresponding matter-wave will have an incredibly small wave-length, because your mass is so much greater than that of the electron: it would take a

milliard billion billion of your matter-waves to make up a centimetre!

Schrödinger, however, has not forgotten his main problem: the atom. It may be stated thus: We know that the atomic nucleus is extremely small. We calculate how far a matter-wave will be diffracted by the nucleus.

A tiny mote, floating in the sunshine, diffracts light. Around the mote arises a luminous, vaguely delimited cloud of light, a "diffraction halo," which is always a few light-wave-lengths in diameter, no matter how small the particle of dust. All the little specks of light which you see shimmering in the slanting rays of the evening sun are such diffraction haloes.

An atomic nucleus, infinitesimally small, diffracts an electron-wave. Around the nucleus arises a vaguely delimited cloud, which is always of the same order of magnitude as the matter-waves—a few hundred millionths of a centimetre. And so, says Schrödinger, *this diffraction halo is the atom.* As you see, Schrödinger has "spread" the electrons over a certain area. Here are Bohr's orbits over again, but only in a vague, allusive, indefinite form.



We can determine the size of an atom by experimental means—not very exactly, of course—and we get a value of a few hundred millionths of a centimetre, such as Schrödinger requires for his diffraction halo. That the size is what it should be is of itself encouraging. But there is more to be said than this. Schrödinger calculates, by means of the celebrated wave-equation, the energy of this atomic cloud. Surprisingly enough, it appears that the energy can assume only certain values! They are almost the values of Bohr's theory—but Schrödinger's energy-values are more closely approximated to the experimental values! They are in complete agreement with the measurements! Schrödinger's fluent, continuous differential equation has explained of itself, by virtue of its mathematical structure, why only certain energy-values are possible to an atom. In this place Bohr had to prescribe his first postulate. Schrödinger needs no postulate.

To us it begins to seem as though such a mathematical

presentation of the quantum laws must be more satisfactory than a subsequently imported demand for quanta as in some sense explaining the laws. We all have the greater confidence in mathematics; we cannot escape the compelling logic of its conclusions. But this is not all.

Here we may quote from *Wallenstein*:

> *Terzky:* The wine speaks in him. Hear him not, I beg you!
> *Isolani:* Wine invents nothing, but it lets things out!

So it is with mathematics. Mathematics invents nothing; it only lets things out. Mathematical formulae can never yield more than was contained in the preliminary statement. Of course, they help us to a complete understanding of the statement. Mathematics is an instrument, a microscope. The greater our mastery of mathematical formalism, the greater the refinement of our technical methods, the more minute and subtle are the physical details which it reveals for us.

The mathematicians have of their own accord developed this formalism as far as possible, without concerning themselves very greatly with its applicability.

So Heisenberg found the "matrix equations" which he needed for his purposes ready-made to his hand, and Schrödinger hit upon a differential equation which had long been known to the mathematicians.

Probability

So there *are* only waves? Matter has been resolved into waves? No—unfortunately, we have been exaggerating a little. The case isn't so simple as that. It did indeed seem at one moment as though, by the means of wave mechanics, and Schrödinger's great equation, which was ready, like a docile "quantum-mill," to swallow everything at a sign from its creator, and discharge it again freshly "quantumated"—as though the ancient dispute would be definitely settled in favour of the wave-theory of the Universe. Schrödinger himself was at first subjected to this temptation. But the dream was soon dispelled.

The matter-waves, as we now know them, are after all not physical realities. They travel in a pure mathematical space

with a velocity greater than that of light—and this alone ought to set us against them. They have been called "guiding waves," and this name is more consonant with the nature of the case. The material particles are in a certain sense the shadows of these waves—mere symbols of these symbols, which move spectrally in cold, sober, mathematical space. And these particles have no will of their own. They must do what the waves prescribe for them. If two guiding waves choose to cancel one another by interference the corresponding particle has simply to disappear!

But the case isn't really quite as spookish as it seemed. We have come to a better understanding of Schrödinger's waves; we know now what they mean. They are a measure of the *probability* of finding a particle at the locus of the wave. If after passing through a crystal the waves show interference-points, this means that here and there and there a great concentration of waves occurs—there many particles are present. Here and there the waves cancel out; there the probability is nil. And we actually do not find a single electron at such points.[1] The peculiar thing is that probability should appear in wave-form; but today the whole science of physics is rather peculiar.

Now, perhaps, you are rather disappointed. You have become accustomed to the unthinkable notion of matter-waves and are beginning to understand them. And now the mathematician comes along with the notion of probability-waves, and makes a clean sweep of everything! What can it all mean?

Well, Schrödinger, too, was disappointed. He had taken the matter-waves to his heart. With great discernment, after much mathematical calculation, he and other research-workers had succeeded in retaining them even in the new theories—real waves of matter, at home in space and time, not in an unlovely mathematical space. But we can no longer follow him in this direction. We see only that both matter and light retain their amphibious character: they are waves *and* particles. The difficult mathematical formalism of quantum mechanics explains in a certain sense how a constant wave-field can

[1] Even light-waves can be so conceived: as a measure of probability that a light quantum will occur here or there.

occasion the appearance of quanta. But apart from the fact that quantum mechanics is far from having said its last word, we see as yet no possibility of an objective conception of its content. It sticks to its "wave and particle." The wave-image and the particle-image are two sides of one and the same thing. Only the two together will give us the complete, objective concept which has indeed been given mathematical expression in quantum mechanics—but no more. And I can do no better than to quote here and now the concluding sentence of Schrödinger's Nobel lecture:

"Hitherto we have not succeeded in comprehending them both in one unitary form. Only in extreme cases does the one or the other connection predominate so greatly that we *believe* we can manage with the wave-image alone, or the particle-image alone."

And a little earlier:

"The question is only whether from now onwards we must abandon the attempt to attach the description, as has hitherto been done, to a definite hypothesis as to how the Universe is actually built. Many thinkers are inclined to make this renunciation already. But I think by so doing one is making things a little too easy."

II. SPLITTING THE ATOM

I am afraid the last chapter was rather too mathematical, too dry, too theoretical. So in conclusion we will take another glance at physical reality: in the laboratory of a physicist who is investigating the nature of the atom.

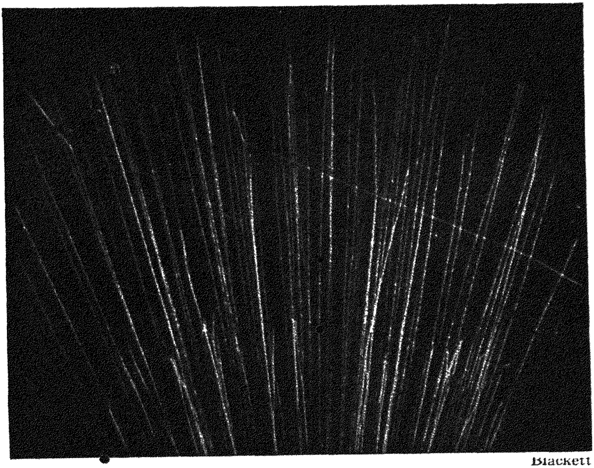
At first there was nothing at all to be seen: it was too dark. Then, for one brief moment, a brilliant light flashed out of the blackness, accompanied by a rending, metallic clang. Again I was surrounded by darkness; but in this moment I had seen a man's face, pale and spectral, and his narrow head,

with knitted brows, like a Japanese ghost appearing in the night. A few bluish sparks, like will-o'-the-wisps, leapt hither and thither in the middle of the room, crackling derisively, and a peculiar, pungent odour filled the air.—"Stop! One moment!" murmured someone in the darkness.—"What are you doing there?" I asked at random.—"I'm photographing an atom!" replied the ghost. The sort of answer one would have expected!

"Very interesting." I said, as politely as possible. It is better not to vex a ghost.

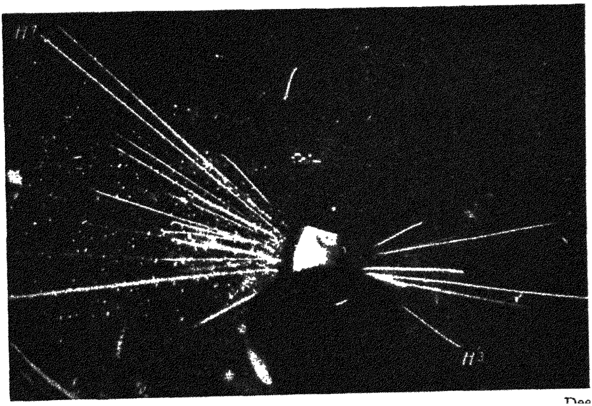
The electric light was switched on, and the ghost became a tall, thin man in a white overall, who was still bending over his apparatus. The serpentine tangle of innumerable glass tubes, the many cables, the glittering brass balls, arc lamps, and the lights reflected from the curiously shaped apparatus,

PLATE 7



Blackett

DISINTEGRATION OF NITROGEN BY ALPHA-PARTICLES

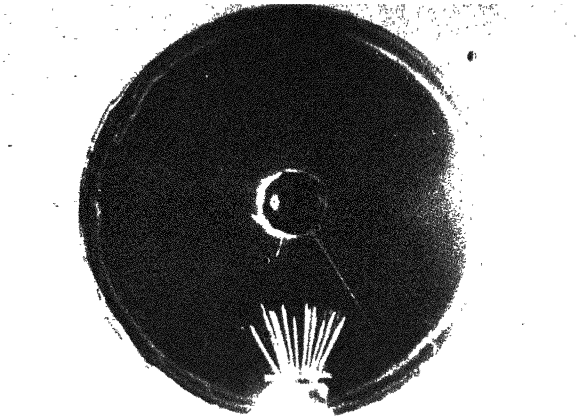


Dee

DISINTEGRATION OF HEAVY HYDROGEN BY BOMBARDMENT WITH SAME

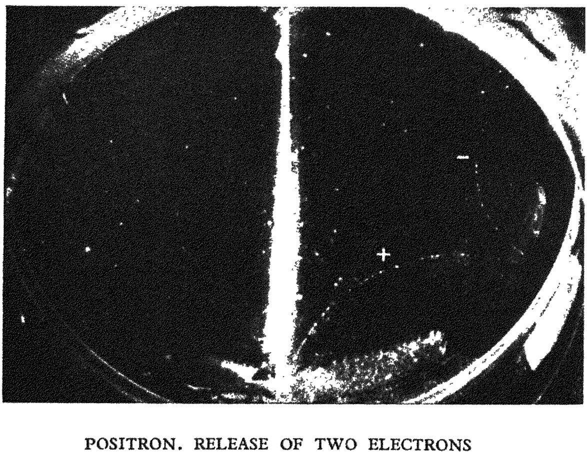
THE SPLITTING OF THE ATOM

PLATE 8



Rasetti

NEUTRONS



POSITRON. RELEASE OF TWO ELECTRONS

many of which were partly covered with black cloths—all this was too much for me. I looked doubtfully round the room, and gave up all hope of understanding what was being done.

But now, as I sat face to face with the magician, my confidence returned, and I smiled politely. "How do you manage to photograph the atoms?" I asked. "I know this much—that atoms are very small, that they lie far beneath the limits of visibility; in short, your assertion seems to be fairly incredible, to use no stronger expression. I don't wish to be offensive. . . ."

"Of course, you are right, the atoms are not very large," the ghost replied, appeasingly. "Nevertheless, it *is* possible to photograph them—and it's really for the same reason that there are such atrocious fogs in London. Fog—you learnt what fog is at school—fog is precipitated water-vapour—milliards of tiny drops of water, hovering in the air. England is an island, and there is plenty of water-vapour in its moist atmosphere. This wanders about in search of something on which it can precipitate itself, and having found it, clings to it as a drowning man to a straw. Well, the London factories yield an abundant supply of the necessary condensation nuclei. There is an abundance of soot and dust above London, and the water-vapour precipitates itself on the little particles of soot. The London fogs are really first-class. . . ."

"And what if there is no soot?" I asked.

"Then the water-vapour looks for something else. Ions suit it well enough; atoms and molecules, that is, which have lost an outer electron.—Well, you know the radium elements emit alpha-particles, positively charged helium nuclei of terrific velocity. Such a swiftly flying alpha-particle robs the molecules of the air which gets in its way. It deprives them of electrons—it "ionizes" them, thanks to its great momentum—so long as its velocity is great enough. It leaves behind it, along its path, a track of ions, and if water-vapour is present, enough water-vapour, it will precipitate itself on these ions, forming drops of mist around them. So the path of the alpha-particle shows itself as a streak of mist. You see, it took an Englishman to hit on this idea.

"The Englishman was C. T. R. Wilson. And his apparatus

is the celebrated Wilson chamber. A big cylinder with a glass lid, the bottom of which can be closed by a movable plunger, and which contains a sufficient quantity of moist air. The plunger is drawn downwards with a jerk; the moist air in the cylinder is thus suddenly cooled, and a state of so-called 'super-saturation' is obtained. The air contains more water-vapour than it can really hold. The water-vapour looks anxiously about for condensation-nuclei—and it finds none in the perfectly dustless cylinder. It is a moment of extreme tension.

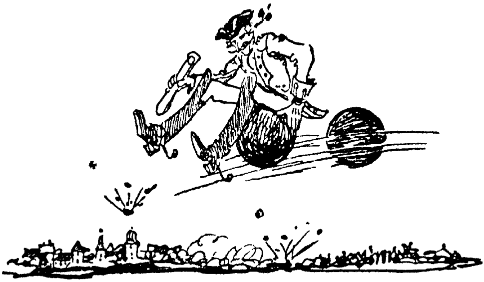
"And at this moment Wilson opens a shutter and allows a hail of alpha-rays to shoot into his cloud-chamber. They rush through the cylinder, leaving trails of ions along their track. This is what the water-vapour was waiting for—it falls upon the ions and instantaneously forms about every ion a tiny drop of mist. At the same moment a switch is thrown, a brilliant lamp is lit, casting a bright cone of light through the side of the chamber, the shutter of a waiting camera, which is fixed above the apparatus, is released with a faint click, and the trails of mist are photographed through the glass lid. These four processes must follow one another with the greatest exactitude, in fractions of a second. For example, it is best that the alpha-radiation should be admitted to the chamber when the plunger has still to travel a quarter of a millimetre to a millimetre and a half of its throw; not more and not less. And one experimenter, Kapitza, has subjected the radiation to a strong magnetic field—sending currents of thousands of amperes for a hundredth of a second through the coils of the great electromagnets which surround the Wilson chamber; and these currents, too, must be exactly fitted into the sequence of operations. The switching arrangements alone are a scientific masterpiece. Yes, it is not so simple to get irreproachable results with a Wilson chamber. But here you see some of the exposures made.

"You see how wonderfully straight these tracks are, and how suddenly they end. The alpha-particle has captured a couple of electrons in its flight, and has compensated its positive charge. Now it is electrically neutral; it can no longer ionize the water-vapour, and has lost its power of creating fog; so

we can't see it any longer. But here is something particularly interesting—a track which suddenly turns aside, making a sharp angle towards the end."

"What has occurred there? What has happend to the alpha-particle?"

"It was a collision. A collision with an atomic nucleus. We know, of course, that matter has an open structure. And a comparatively heavy, very violent projectile, like the helium nucleus, the alpha-particle, flies practically unhindered between the atoms; indeed, it will even penetrate the atom itself without



anything happening, flying through the electron-shells of the nitrogen atoms contained in the air of the chamber. The light, negative, spinning electrons haven't the strength to stop the rushing alpha-particle. Fire a charge of shot through a dancing swarm of midges—do you think a pellet, even if it happened to strike a midge, would allow itself to be deflected from its rectilinear course? All that would happen, at most, would be that the midge would be violently hurled aside. It is the same with the electrons.

"Münchausen tells us of a collision between two cannon-balls in the air, and in the Great War it may really have happened now and again that two projectiles collided in their flight. Certainly such cases are not frequent; but once in a thousand or ten thousand times it may really happen, and then, of course, even a cannon-ball would be considerably deflected. —And here, in this picture, is such a Münchausen incident. Here the alpha-particle flew straight at a nucleus, the

nucleus of a nitrogen-atom. This nucleus is almost four times as heavy as the alpha-particle, and in its immediate vicinity is a very powerful, concentrated electric field. It can—and usually does—happen that the alpha-particle shoots past a little to one side of the threatened danger. It is then seized by the electric field and deflected. But it may happen that it strikes the nitrogen-nucleus such a violent blow that this also flies off with great velocity, quickly enough to ionize the air itself, and conjure up a streak of fog. If such an incident is successfully photographed it will be seen that two tracks proceed from the site of the collision—the track of the particle is apparently forked. But the collision is not always a glancing blow. Sometimes the alpha-particle rushes straight at the nitrogen-nucleus, aiming directly for its centre. Avoidance is impossible; and this collision has serious consequences."

My informant paused for a moment. "I am sure you can guess what the end of my story will be—the legendary splitting of the atom! A conception, as you know, which has caused so much sensation, such wild speculation, that the majority of scientists become rather restive if the matter is mentioned; and as a rule they have only one request to make: Please, if possible, leave us out of the question! We are making our experiments, we are trying, with all our might, with all the acumen of our best thinkers, to decipher the problem of the structure of the atomic nucleus and the secret of its disintegration. As for what consequences our work may have in the matter of producing economical energy, if it does have any practical results at all—we leave it to others to think of such things. We are interested only in the scientific problem."

He looked at me inquiringly, and I nodded in approval, but not with a perfectly easy conscience. To me, at all events, the practical aspect of the problem seemed at least equally interesting. But I kept my thoughts to myself.

"And how did all this begin?" I asked innocently.

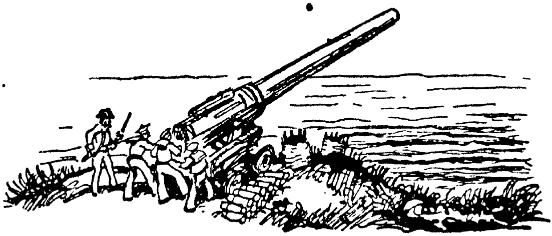
"The story begins with a stirring title," answered the research-worker.

"Rutherford opens fire"

"RUTHERFORD again?"

"Again. Rutherford's genius, as a matter of fact, has anticipated most of our fundamental ideas. What with the synthesis and further development of his ideas, and the solving of all the individual problems which he has stated, he has provided work to keep a whole generation of research-workers busy. But to begin with—it was he who opened fire. This was in 1919.

"You could build a giant cannon, a 'Big Bertha,' on the coast, and simply fire at the sea, in the vague hope of hitting a ship one day. What do you think about that?"



"Not much chance, eh? No, I don't think that would be very successful. Perhaps if you set up a battery of a thousand guns and fired a dense hail of shrapnel . . ."

"Well, that was very much how Rutherford proceeded. He fired a dense hail of alpha-particles out of a radio-active substance—it was Radium C, the most concentrated source of energy we possess—into a vessel filled with nitrogen. Ten thousand, a hundred thousand shots were hurled into the nitrogen atmosphere. And do you know what Rutherford suddenly discovered?"

"I've no idea!"

"Well, you could hardly have guessed—it was hydrogen! Lord Rutherford noted 'hydrogen-radiations'—travelling with great velocity and covering long distances—hydrogen nuclei —that is, protons!"

"Where on earth did the hydrogen come from? I thought the vessel contained nitrogen?"

"So it did, and Rutherford found himself obliged to draw a novel and surprising conclusion—and he wasn't a man who would refuse to accept the results of his experiments, no matter how monstrous they seemed. The hydrogen came from the nitrogen! Thousands and tens of thousands of shots had gone astray or been deflected. But at last one of the alpha-particles flew full at a nitrogen nucleus. The collision, the disaster, couldn't be avoided—a bull! The coastal battery had hit a steamer on the watery waste of the ocean! The alpha-particle registered a direct hit on the nitrogen nucleus, and the nitrogen nucleus, that spurious compound of protons and neutrons, could not stand the blow; a proton, a hydrogen-nucleus, was hurled with elemental violence out of the nuclear structure. A masterless proton, a hydrogen-ray sped through the vessel.

"Disintegration of the atom! For the first time it had been artificially effected: the privilege of the radioactive elements was infringed! Man had found a means of exciting the disintegration of the atom in the laboratory; by virtue of his arts he could command at will the transmutation of nitrogen into hydrogen! The thing of which the alchemists had dreamed for centuries was translated into fact in the faint flashing of the fluorescent screen under Rutherford's microscope!

"Subsequently the physicists went even farther than Rutherford—they photographed the alchemists' dream. P. M. S. Blackett at Cambridge succeeded in obtaining the first photographs of disintegration—graphic documents, records of the destruction of a world in little. Twenty-three thousand exposures he made with his automatically repeating Wilson camera. 415,000 alpha-particles were photographed in movement. And eight cases of disintegration were found in the films. Eight exposures out of 23,000, in which it can be seen how the liberated hydrogen-ray shoots out into the wide world!" (Plate 7.)

Huxley has compared the research-workers of our days with monks, who, buried in their monasteries, forgotten by the world, pass their lives in fanatical devotion to the mysterious rites of their science. But reflecting on this, I asked myself: Had any monk of the Middle Ages the uncanny patience, the

fanatical perseverance demanded by this work of Blackett's, which wins a prize after fifty thousand failures?

"Disintegration of the atom," continued the scientist. "Explosion of nitrogen. Artificial release of the terrific energies which must be available in the atomic nucleus. . . ."

Suddenly I found I was no longer following his words. In my mind's eye I saw a terrible picture, of which I must have read somewhere, at some time.

In the nineteenth century a French research-worker set to work upon a tremendous experiment. He wanted to set fire to the air. In the electric arc he induced the nitrogen and the oxygen of the air to combine. The experiment succeeded—but a moment later the scientist, seized with horror, rushed from the laboratory with chalk-white face, distracted, terrified. What if the air had continued to burn? If it had not been extinguished immediately, if the conflagration had persisted, as when a wax taper is lighted, if the fire had burst out of the laboratory, invading the atmosphere, and had raged with elementary violence over the globe!—The Earth would have been one glowing ember, its inhabitants asphyxiated and carbonized!

Did such thoughts occur to Rutherford? We do not know what he felt after his nitrogen experiment; but perhaps his satisfaction was tinged with some such horror. What would have happened if the nitrogen-atoms had exploded?

"What would have happened then?" I almost shouted the words in the face of the quiet, serious man who was sitting opposite me. "Tell me—what would have happened then?"

"When?" he replied, unmoved and matter-of-fact. "What should have happened?"

"If the nitrogen-atom had exploded!" His untroubled calm and assurance annoyed me. Surely he knew what terrible thoughts were tormenting me—surely he could guess the reason of my excitement? "Do we know anything at all about the real energies of the atomic nucleus?"

"No," he replied. "We know only one thing—wherever they reveal themselves, as in the radium metals, they go beyond all human standards. Of course, such a thing might have happened under certain circumstances. . . . Rutherford, with his bombardment, might have unlocked an invisible store-

house of energies of quite unsuspected violence. There are substances—aluminium, for example—which are of such a character. Substances which when they are bombarded by alpha-particles hurl protons out of their nuclei which have greater energy than the alpha-rays which unlock them: just as a munition store can be made to explode by a small bomb, when it will hurl heavy shells into the air in all directions, and with devastating force. Concealed atomic energies are liberated here whose magnitude we cannot predict before experimenting. The energy of a few grammes may suffice to shatter the whole apparatus, the whole laboratory—perhaps in a fraction of a second, by a chain of explosions, to lay whole cities and countries in ruins—perhaps to rend the entire earth into atoms with one avenging explosion. We don't know.

"Or the conflagration might eat its way slowly, cancer-like, from atom to atom, in deadly, mysterious silence, irresistibly reaching out in all directions. Perhaps the disintegration could no longer be checked by human means—any more than we can influence the disintegration of the radio-active atoms. And so the conflagration would spread before our terrified and helpless eyes, extending itself with malicious deliberation, until the whole earth was a red-hot ball.

"Well, such speculations do not greatly trouble the research-worker. We don't know for certain, but we don't really believe such things will happen. Think of Blackett's 415,000 shots with eight hits! How great is the probability that one of these eight artificially generated hydrogen-rays should in its turn achieve a hit? It is so ridiculously small that we needn't, for the time being, trouble about it. Day after day, hour after hour, the scientists are striving to increase the energy of the bombardment. The natural radium rays are no longer sufficient. The hail of bullets must be made denser and denser, and since radium is not available in sufficient quantities, rapid radiations are produced artificially. Really, of course, this is a question of prestige. One is glad of Rutherford's success, but one doesn't regard it as being absolutely fair, as it was won, so to speak, with the enemy's weapons; since the radiations from Radium C are 'natural' rays. Only the result of a bombardment in which the projectiles are artificially generated can

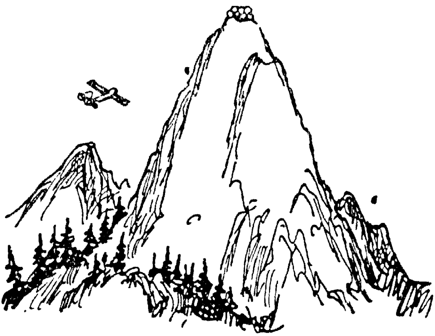
really deserve the title of 'artificial disintegration of the atom.' And today we can produce it."

"What do you think—shall we, really, ever get so far—as far as the technical exploitation of atomic energy?" I asked, forgetting my mental reservation. "After all, it would not be the first time that serious and unworldly investigators have suddenly approached the engineers and industrialists with new possibilities, great opportunities, saying: Kindly help yourselves! Presently, perhaps, in every quarter of the city, there will be huge boilers whose furnaces will be filled with stones and rubbish; then the District Atom-Disintegrator would approach, and after an official welcome he would turn his great radiator on the stones and pull the lever. A bluish light, a pungent smell of ozone, a slight hissing sound, and the first stone would crumble. The atomic disintegration, thus initiated, would begin its work; the engineers would feel its heat in their faces. The District Disintegrator would go his way; the stones in the furnace would glow and smoulder and gradually disintegrate. The boilers would have been fired for another year.

"Or perhaps you will make us a little radiation-chamber, which will employ the cosmic rays to disintegrate the atom. And a man of the year 2000, exploring the desert, perhaps, or in some inhospitable mountain country, will take his disintegration-generator from his pocket as we take a cigarette-lighter, gather a handful of pebbles, set them alight with a yawn—and call to his companions: 'All right, boys, the cars can go on, we've filled up!"

The scientist laughed and lifted his hands defensively: "No," he said, "you have a rather short memory. Have you forgotten already what we decided, in connection with Blackett's experiment, would be the probability of a disintegration? Do you know what Lord Rutherford has said? 'Anybody who was seeking for a source of power in atomic disintegration was talking moonshine.' Of course, one should never say 'never.' Is it so long since we thought it impossible to split atomic nuclei with tensions of a few hundred thousand volts? We thought millions would be necessary. In Germany, in England, in America, the physicists applied themselves to

generating these millions of volts and building discharging-tubes which could resist them. Cockcroft and Walton, of the Cavendish Laboratory in Cambridge, were among them. They say that one day Lord Rutherford exclaimed: 'Now, you've really been constructing long enough. Try it just for once; try it with a low tension!' And the two young Englishmen switched the current on to their discharging-tube—the tension was 100,000 volts—and this potential ran through the protons which were employed as projectiles, and they dashed against a lithium target."



"100,000 volts—but that is almost nothing at all! Why, industry employs such voltages nowadays!"

"Of course, until 1931 everybody thought the experiment would be perfectly hopeless. But Cockcroft and Walton disintegrated their lithium atoms at the first blow—and in unprecedented numbers."

"And is there any explanation for that?"

"Yes—today we have very definite notions of what happens. Think of the seven protons and the seven neutrons which together make up the nitrogen nucleus. Earlier, perhaps, one might have thought that these seven protons were sitting all together on the top of a high mountain, surveying their kingdom, and ruling their seven subjects, the circling electrons, with a firm hand? Any intruder who attempted to disturb their exalted peace, any cannon-ball that sought to destroy the harmony of the system, must have at least enough energy to

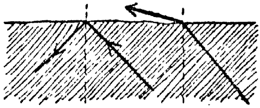
roll up the steep mountain; and you can imagine that the majority of shots, which would strike it a little askew, would be deflected from their original course and would roll harmlessly past their target.

"Well, this picture isn't quite exact; the rulers aren't sitting in lordly freedom on their towering crag—they themselves are prisoners. The mountain is a volcano; far below, at the bottom of the crater—below the level of the ground!—the protons and neutrons are assembled. In a narrow hole, a billionth of a millimetre in diameter, they are tearing round and round—their velocity may be as great as 10,000 kilometres per second—if we are justified in applying such notions of the outer world as 'velocity' to the inside of such a hole.

"The rulers over the electrons are themselves prisoners; their own prisoners! Do you understand what I mean? This volcano exists merely as a result of the strong positive charge of the protons, by whom this monstrous 'potential barrier' is thrown up; and since the projectiles, the alpha-rays, are themselves positively charged, and two positive charges repel each other, they can't get the better of the mountain. Merely for illustrative purposes it is convenient to proceed as though the protons and neutrons were free, and cast into this hole by some mighty spirit. A sort of self-deception on the part of the protons! The height of the barrier amounts to some millions of volts."

"Then this tension will be necessary! A few million volts! The ball must surely be able to roll up the mountain—it can't, after all, burrow its way under it!"

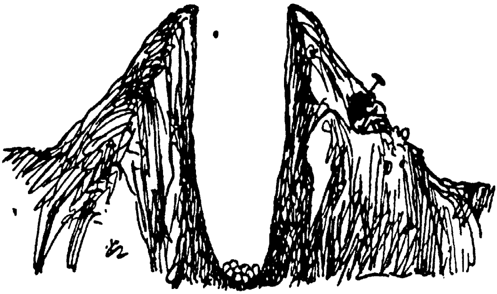
"Well, that is precisely the surprising result of wave-mechanics. Once again, you must blindly trust the wave-theory. You know how a light-ray is 'totally' reflected. When it emerges from glass into the air it is refracted; and if the angle at which it strikes the delimiting surface is great enough



it will be so far refracted, so to speak, that it will return into the glass: it will be *totally* reflected—more completely than the best silvered mirror could reflect it. This is the principle

of the inverting prisms which twice invert the light-rays in a prism binocular.

"The optics of radiation tells us, then: a light-ray which strikes on a limiting surface at a smaller angle than the limiting angle is there totally reflected. But it doesn't tell the truth! Even Newton knew this, though he couldn't properly explain it. Only the modern wave-optics knows the truth: the wave always penetrates a very little way into the air—it enters into regions which according to ray-optics should be prohibited! Of course, as an ordinary thing the wave does not long survive the consequences of its presumption; its strength fails very



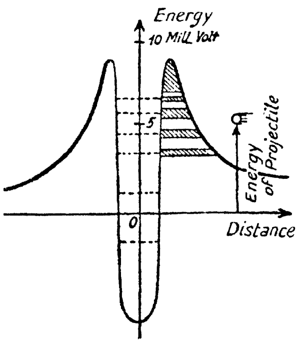
rapidly in the prohibited medium; falling almost to nothing after a few wave-lengths. Imagine, in the place of the limiting surface, the steep potential-mountain; and now consider that we are comparing ray-optics to the old mechanics.

"The old mechanics says: A shot that runs against a potential-mountain with too little velocity turns before it reaches the top and runs back again; it is elastically reflected. Every particle that has more than the necessary limiting velocity tops the mountain and falls into the hole. But the old mechanics does not speak truly! Only the new wave-mechanics knows the truth; the matter-wave always penetrates a little way into the potential-mountain; if it is thin enough it can penetrate it with perceptible violence; it enters regions which according to the old classic mechanics should be prohibited. The matter-wave penetrates—greatly weakened, of course!—the potential-mountain; and if, once more, we regard it as a measure of

probability, we can say: Even with insufficient energy, with a velocity under the limit, the shot has a certain probability of getting into the potential-mountain; it 'digs itself a tunnel through it.' And like its shadow the corporeal particle follows, as we know. This is the celebrated 'Gamow tunnel-effect.'

"The situation is even slightly more favourable. It seems as though the rock of the potential-mountain were not everywhere equally hard; as though at different heights there were places of greater and less penetrability. We must reflect that the shot has got to remain somewhere in the nucleus, and since Bohr's time we have grown cautious. We must assume that even the atomic nucleus, like the atom as a whole, can exist only in certain stages of energy; so that here too the intending shot must seek for itself a step of the staircase; it doesn't simply fall to the ground.

"It is more or less intelligible that a clever shot would so locate its tunnel that it would land exactly on such a step. In this case the probability of penetration is at its maximum. A swifter shot, one with greater energy, whose tunnel lies higher, and which has not landed on an energy-step, will have a smaller chance of bringing about a disintegration than the slower shot. This seems perfectly nonsensical, but Chadwick has really been able to show that on increasing the velocity—the energy of the shot—the results are smaller, but that they increase again at the next energy-step.



"If I attune my radio receiver to Berlin only this wave-length is heard; all others, whether louder or fainter, have, so to speak, too small a probability of setting the tuning circuit in oscillation, and so entering the apparatus. But the atomic nucleus, according to wave-mechanics, is tuned to a few frequencies—those which correspond with its energy-values, its 'individual oscillations.' And the shot itself, of course,

corresponds to a wave—according to Schrödinger. It is clear that just those waves with the attuned frequency will penetrate easily. Like the Prince in the fairy-tale who entered the castle which whole armies had tried in vain to capture, because he knew the magic word—so the projectile knows the magic word. It is: individual oscillation.

"Gamow was able to explain radio-activity by his theory; this is, so to speak, the converse of bombardment—an attempt to get *out* of the volcano. According to the classic mechanics the alpha-particles—products of two protons and two neutrons, as we know—were condemned to sit forever imprisoned in their potential-hole. But wave-mechanics gave them a faint glimmer of hope—very faint, of course, in correspondence with the little strength of the probability-wave on the other side of the threshold. But they come again and again, trillions of times a second they assail the mountain, and one day the great blow is struck. The alpha-particle breaks through the wall, comes into the open on the other side, and shoots with great velocity—10–20,000 kilometres per second—out into the world. The Wilson chamber shows its course.

"It may seem rather rough on the alpha-ray that Lord Rutherford should harness it for his disintegration-experiment after it had won its freedom. Either it flies past—when its existence is purposeless, and its master is vexed; or it strikes a nucleus and breaks through the potential-threshold—and then it is captured anew: as a rule for life.

"But it is just this second case that we have got to consider if we want to solve our problem. The alpha-particle—in Rutherford's experiment, or the proton in Cockcroft and Walton's—has penetrated the crater; but there they are by no means pleased with its company. The tension is so great that the whole nuclear structure is in an over-excited, 'stimulated' condition. There are too many in it; one must give way. And after an imperceptibly short lapse of time a proton has the wisdom to give way, and a hydrogen-ray is emitted. There it is!

"It may happen that the residual nucleus now remains in a state of rest—that the expelled proton takes the disturbing surplus energy with it, leaving behind it a stable nucleus. But

other cases are conceivable. We have already progressed a good way in 'nuclear chemistry.' I can give you yet another example which is illustrative of Cockcroft and Walton's experiment; it also illustrates the boldness—I could almost say the insolence —of our modern way of dealing with elements: Here it is:

$$_1H^1 + {}_3L^7 \rightarrow {}_4Be^8 \rightarrow 2_2He^4$$

"In words: The projectile H,[1] a proton of high velocity, penetrates into a lithium-nucleus of atomic weight 7, and charge 3; for a moment they are all together, and we have a 'stimulated' beryllium-nucleus; but it is not properly stable, and after a fraction of a second it breaks up—into two alpha-particles, which fly off in different directions with great velocity. Out of hydrogen and lithium we have made helium!

Rutherford and Oliphant bombarded heavy hydrogen—the 'hydrogen-isotope' of atomic weight 2—with heavy hydrogen. This hydrogen is so important that it has been given a name of its own: Deuterium or Diplogen—unfortunately the scientists have not yet come to an agreement on the point. The heavy hydrogen nucleus is called a "diplon," and is denoted by the symbol $_1D^2$. The nuclear reaction then reads:

$$_1D^2 + {}_1D^2 \rightarrow {}_2He^4 \rightarrow {}_1H^1 + {}_1T^3$$

or in words: The diplon projectile penetrates a diplon and forms a helium nucleus, which immediately disintegrates—into ordinary hydrogen H and a 'triplogen' nucleus, $_1T^3$, a 'heaviest' hydrogen of atomic weight 3 (Plate 7). The possibilities seem inexhaustible.

"Yet another example: Irène Curie, the daughter of Marie Curie, and F. Joliot, her husband, made the following discovery: If Bor is bombarded with a strong alpha-radiation from polonium, nitrogen and a neutron are obtained, according to the formula—

$$_5B^{10} + {}_2He^4 \rightarrow {}_7N^{13} + {}_0n^1$$

"This is something new: for not one of the known radioactive elements emits neutrons. But this is not all. The nitrogen

[1] The number on the right, above the line, signifies the atomic weight, the number on the left, below the line, the nuclear charge.

which is thus obtained is radio-active! It is an unstable nucleus with a half-value period of fourteen minutes; and even in its disintegration it reserves a special surprise for us: neither α nor β disintegration occurs, but the "radio-nitrogen" shoots out a positron, a positive electron, and therewith transmutes itself into *carbon*!

$$_7N^{13} \rightarrow {}_6C^{13} + e^+$$

"The carbon appears to be stable.

"Artificial radioactivity! If we had not had experience of so many and such amazing novelties during these last few years we should hardly have believed this new discovery to be possible. But it is so—and the whole of physics finds itself in a state of revolution. In one year we are discovering more than we used to discover in decades. Curie and Joliot, with their concentrated preparation, obtained about a billion alpha-particles per second; and every ten millionth caused a disintegration. Thus a hundred thousand atoms of radio-nitrogen were generated in each second. For the first time the two investigators were able to obtain even chemical evidence of the nitrogen, and so furnish the final proof of disintegration, if any was still needed."

"But why doesn't the projectile, the helium-nucleus itself, break down?"

"That is explained by the theory of relativity. You know already that mass and energy mean the same thing, that mass is only 'energy on deposit'? Well, a helium nucleus consists of two protons and two neutrons. It is true that the sum isn't quite correct—the four together weigh *more* than the helium nucleus; in the ordinary way the weight of the proton is 1·008, and that of the neutron 1·0008, so that the sum of the four weights is 4·032; and the helium nucleus weighs only 4·000. But this very discrepancy becomes a cause of rejoicing. For the protons and neutrons in the helium nucleus were improvident—they changed their safely-invested mass-capital into liquid capital, and spent some of it in energy-radiation. Now they feel the lack of it—now they are prisoners for ever. One would have to supply this squandered 0·032 of energy from without, as a generous gift—then one could purchase their

freedom; then they could face the world again with their true mass, their properly invested capital. So long as no one gives them the necessary energy they must remain together. The 'mass defect' is the reason why the helium nuclei are so durable and so well adapted for use as projectiles. If, conversely, we could somehow compel two protons and two neutrons to form a permanent union, we should obtain this very 'mass defect' as energy. But, as you see—the artificial helium nucleus which Rutherford and Oliphant created (p. 303) disintegrates at once.

"From the depths of the starry Universe a mysterious radiation comes to us, the *cosmic radiation*, discovered by Hess and Kolhörster. It is richer in energy than any radiation of which we know. Even at the bottom of the Bodensee—in 130 fathoms of water—Regener was able to prove its action. It is just intense enough to be recorded; we have as yet no real information as to its nature—our terrestrial resources are as yet inadequate. Its wave-length is even shorter than that of the hardest γ-rays. We do not as yet know what natural process could provide the energy for such radiation; but the hypothesis has been advanced that far away in the heavens, enormously far, mass is 'radiating itself away'—transforming itself into energy, and so producing the cosmic rays. An hypothesis which, at all events, has not as yet been refuted.

"We need not go out into space, however—here before us, in the Wilson chamber, the same thing is happening! Even here, in our disintegration experiments, a fraction of mass is transformed into energy—apparently disappearing, to reappear in the frantic flight of the alpha-particles through the cloud-chamber. Ten thousand kilometres per second! Think what that means! The energy of my Thorium C alpha-rays amounts to 2·6 million volts!"

I looked about me rather nervously. I saw no mighty, crashing discharging-condensers, no yard-long sparks, no armoured and protected observers' posts. The actual disintegration-chamber was small, handy, and inconspicuous. There, in that little metal cylinder, worlds perished, atoms transformed themselves, matter disappeared. . . .

"It is always a fresh surprise," I said, "to realize how quickly

people become accustomed to the unprecedented. People talk excitedly of atomic disintegration, painting the most lurid pictures, and we predict, in ever more impressive terms, how one day humanity will perform this miracle. And in the meantime here you sit in your laboratory—like a few dozen or hundred other scientists in all parts of the world—quietly destroying millions and millions of atoms—just as you would read an electrometer, in just such a matter-of-fact way.' "

"True," replied the scientist. "But that isn't all. Recently we have discovered a way of abolishing the potential mountain, in a certain sense.

"It came into being—you'll remember—only through the mutual repulsion between the positive nucleus and the positive projectile. But if I use an electrically neutral projectile, a neutron, *there is no repulsion.* A neutron encounters no opposition—it knows nothing of danger, and in that way overcomes it. For the neutron nothing is left of the whole mountain, excepting the crater—so it doesn't need to dig a tunnel.

"Fermi was the first to exploit this possibility—though Fermi is really no experimenter. Lord Rutherford has said that 'Fermi, a theoretician of the first water, has spontaneously transformed himself into an experimenter.' In the region of radioactive transformations all things are possible. With the aid of an intense bombardment of neutrons Fermi and his collaborators have succeeded in disintegrating more than forty elements; and the sensational thing about his experiments is that uranium was among them! Uranium, of atomic weight 92—the last element in the Periodic System! On being bombarded it swallows the neutron and disintegrates by emitting a negative electron—*it transforms itself into an Element* 93!

Perhaps these experiments have not been absolutely verified —but they seem to be deserving of confidence. If they are really what they seem to be, then Fermi has for the first time produced an element which has never yet been found in Nature—which has perhaps never existed in a free state! Apparently the physicists are trying to improve on Nature!"

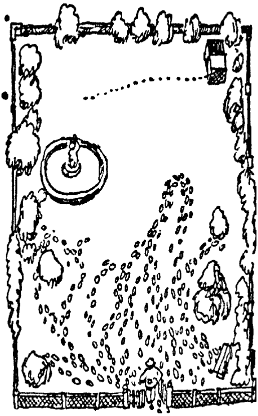
Here I could only shake my head.

"But I wanted to ask something else: about the neutron. How can you discover it at all, how verify its existence, if it

can't betray its presence in the cloud-chamber by an electrical charge and its ionizing influence?"

"Ah, the neutron—that's a real detective story! The hero is Chadwick, a pupil of Rutherford's. And this is how the story goes:

"Chadwick discovered a great number of footprints in his garden, close to the entrance-gate. That was all right—they were the footprints of his guests, whom he had invited. They had scattered about the garden; but they had not gone much more than half-way up it. Suddenly he found, right at the other end of the garden, a single narrow trail, made by a dog from the kennel. But who on earth had let the dog loose? It couldn't be any of his guests—for then he could have followed his track to the spot. And the garden was enclosed by high, impassable walls. Chadwick was faced with an enigma. How had the man contrived to cross the garden to the kennel? It must have been an invisible man; more, a being who left no footprints behind him! The Great Unknown in pure culture! A being who leaves no trace of his passage? Chadwick shook his head as he returned to the house. This hypothesis seemed too audacious. . . .



"The Wilson chamber photograph (Plate 8) shows this: a series of normal tracks of alpha-particles. And then, beginning right at the other end, a fine hydrogen track, a liberated proton. And not a single alpha-particle, recognizable by its trail, that could have set the proton free. Chadwick lit his pipe, pulled his cap over his forehead, and began to think hard. This Great Unknown must be pretty strong to open the heavy door of the kennel—and throw the hydrogen-nucleus out. So it must have been moving quickly. Nevertheless, it leaves no traces—so it doesn't ionize the air. So there was no charge—it must

have been an electrically neutral particle. This was the only explanation: A neutron existed. Its mass—Chadwick could estimate it pretty accurately—was almost equal to that of the proton. There is a heavy particle of the weight of the proton, but without charge, said Chadwick decidedly, knocking out his pipe.

"At first the physicists shook their heads. Then they fell with fiery zeal upon the new discovery. First it was beatified, then sanctified. It was passed as physically possible, although it completely upset our established notion that nothing but protons and electrons existed. And the physicists found it enormously useful—a marvellous support for the nuclear-theory, which was now able to dispense with electrons in atomic nuclei—always a rather unacceptable hypothesis! In the neutron they had an ideal means of increasing the weight of a nucleus to any figure without at the same time increasing its charge. These physicists had suddenly been supplied by Chadwick with ballast to be used on their flights into theory. They helped themselves with both hands. But the neutron, which after all can be explained by the very close association of a proton and an electron, by a fusing of the two, was not the worst. In the same year Anderson, in Chicago, discovered a phantom.

"Yes; Anderson not only saw a ghost—he even photographed it. A light particle in the Wilson chamber, which in appearance, curvature of track, and mass was exactly like the electron —but which was positively charged. A positive electron, a *positron.* At that time this notion seemed the acme of insanity —but there was one man who had been waiting for it: Dirac, in Cambridge. 'Hurrah!' he cried: 'At last! For years my theory has been waiting for the positron!' And then followed Dirac's story of the hole in the Universe. 'There are many electrons in the Universe,' he began. 'They all have a certain positive energy; they all have a certain weight; and since according to Einstein energy and mass are the same, every individual electron has always, at all events, its "energy of mass": about a millionth of an erg. (The erg is the unit of energy.) Whatever an ordinary electron may do, its energy can never sink below this value; indeed, it will usually be greater, since the

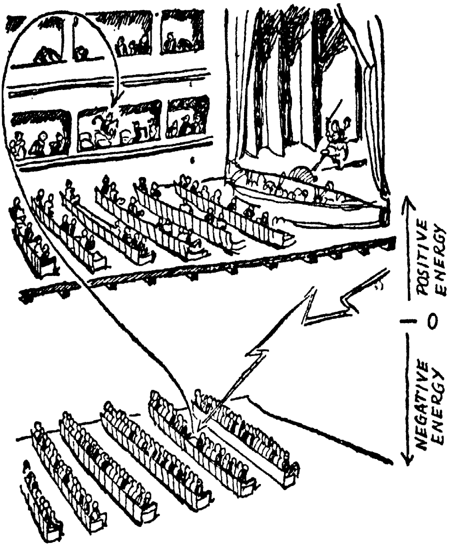
electron moves, and kinetic energy will be added to its mass-energy.

" 'But my theory—from which, by the way—and this is greatly in its favour—the spin of the electron can be readily ascertained—my theory demands, for reasons of symmetry, electrons with *negative* energy. Negative energy, be it understood—don't confuse it with negative electrical charge. A pity that I can't produce such an electron. An electron with negative energy is a very queer thing—more than queer. If I hit an ordinary electron from behind it travels faster. The electron with negative energy travels more slowly; it slows down all the more obstinately the more I hit it, and it runs away if I want to pull it towards me. Gamow has proposed to call these electrons "donkey-electrons," on account of the analogous qualities of the familiar animal!

" 'You will object that nothing so absurd exists or was ever yet observed in Nature. Nevertheless, I have done my theory a good turn. I have put a certain number of places at the disposal of these electrons. And I have done something else. I have assumed that the whole of the stalls provided for negative energy are already occupied. These stalls are in the cellar, under the ordinary theatre. On each chair squats a negative electron with negative energy; the whole area of the stalls is one dense, grey, uniform mass. And since we can see and understand only *differences*, since when everything is uniform we can just as well say "there's nothing there"—so, as an ordinary thing, we see nothing of these sunken stalls far beneath us. But—a catastrophe may occur. A flash of lightning may strike the stalls and fling out one of the grey, identical stall-holders. A gap is left—an unoccupied place. A hole.

" 'Two conditions, of course, must be present. The flash of lightning must possess energy enough, not only to penetrate to the sunken stalls, but to fling one of the grey little occupants upstairs into the ordinary stalls, or one of the boxes—for after all, he must be somewhere. And the lightning must find some counterpoise, something that will cancel its impulse. Anderson was able to supply both. An energetic flash, a cosmic-ray quantum. And a counterpoise, a heavy nucleus. The flash fell—and left a gap.

" 'It may be imagined that the spectators in the cellar would not remain undisturbed. Each of them wanted to sit on the empty stall in turn. And first the right-hand neighbour moves to the left. Has the gap disappeared? No—for now the other chair is unoccupied; the gap seems to have moved one place to the right. And so it continues. A spectator who was sitting



five places away jumps into the empty seat—and now the gap has made a jump of five places. The hole can't be done away with; it moves hither and thither about the cellar-stalls. But it always moves in the opposite direction to the moving spectator. *It behaves exactly like a spectator with his mathematical sign reversed.* The hole in the realm of the electrons produces an external effect exactly like that of an electron with negative signs—like a positive electron.

" 'Once again: As an ordinary thing we know nothing of the realm of electrons of negative energy, because all the places are full. The lightning-flash falls and forces an electron "upwards" out of the sunken stalls. Now we can observe it, as a

normal, negatively charged electron. At the same time, a gap occurs—and this too can be observed, because it involves an *interruption*, a difference in the homogeneous gathering. It behaves, as I have said, just like a positively charged electron; we call it—a positron.

"So this hole drifts about the world—until a surplus spectator jumps into it from 'above.' Then there is peace downstairs. As an equivalent, so that nothing shall be lost, the liberating flash is generated anew. A radiation occurs; but for this reason the spectator and the gap, the negative and the positive electron, disappear from the region of things observable. In plain words: It is possible that an oscillation-quantum, on striking against a nucleus, generates a negative and a positive electron—an electronic pair. The energy necessary to do this is about one million volts. And the contrary process too seems to occur—a positive and a negative electron unite, amalgamate, and disappear, and in return a radiation—a quantum—is produced. This is Dirac's theory.' "

"It sounds uncanny, doesn't it? Highly mysterious."

"Perhaps it does: but since Anderson's observation it is no longer a theory. I have here a photograph in which you can see how, suddenly, *out of nothing*, the cosmic-ray quantum creates an electron and a positron—a gap; and how, by reason of their different charge, they are both deflected in different directions by the magnetic field, and fly off with great energy (Plate 8)."

The New View of the Universe

"Our conceptions of matter, of its 'reality,' are rather different from yours, out in the world. I see no difficulty in the notion that energy can disappear and mass appear—or that mass can dissolve into energy. Dirac's procedure in particular is characteristic of modern physics—of the fundamental change in our way of thinking. Before 1900, for example, no physicist, even in his dreams, would ever have thought of such a thing as negative energy; he might as well have spoken of a 'negative distance.'—'The distance between the two trees is minus four yards!' A theory that yielded such results would have been condemned out of hand as false.

"Today we are more cautious. We know that the classic physics has failed in the attempt to fit the micro-world of atoms into our crude everyday scheme of things, to reconcile it with such concepts as distance, locus, velocity, etc.—in short, to make it objectively conceivable. Bohr's atomic model was the last valiant attempt, and you have seen that he had to make quite unintelligible supplementary requirements. By about 1925 the physicists had begun to learn by experience that Bohr's explanation was impossible. We can't get at the truth of the atom by means of forming conceptions which are borrowed from the world of experience, any more than you can make or mend a watch with a cold chisel and a sledge-hammer. Heisenberg coined the necessary slogan—'the renunciation on principle of visualization.'

"In Heisenberg's 'indeterminacy-principle' Nature seems, with the greatest cunning, to have found a means of making all observations impossible beyond a certain limit—of leaving all our most ingenious questions unanswered. Even the Michelson experiment was such a question—even there Nature seemed with malice aforethought to have effaced every trail which might have betrayed an absolute motion. But Nature is not really as ill-natured as she may seem; the truth is, probably, that she is indifferent to us. All her alleged cunning becomes apparent only when we inquire into something *which does not exist.* And it was from this perception that Heisenberg developed his theory: We can't see into the interior of the atom.

We may attempt to treat the world of atoms *objectively* as formations in time and space, as we are accustomed to do in respect of the locus and orbit and velocity of the electron. But then, immediately, the indeterminacy-principle begins to operate; we have to surrender strict causality—because the electron itself doesn't seem to know what it wants—and content ourselves with statements of probability.

Or we can insist on strict causality; quantum mechanics is prepared to do so; there is nothing indeterminate about its mathematical symbols; but then we must sacrifice objectifiability, representation in space and time. Heisenberg expressed this state of affairs in a concise scheme:

Classic Physics	Quantum Mechanics		
	either	Statistical connection	*or*
Objectifiability (space and time)	Objectifiable		Non-objectifiable (Mathematical schema)
Causality	Subject to Indeterminacy-principle		Causality

"Objectifiability and causality lie on different sides of the balance—when the one rises, the other falls; or, as Jeans says, the two are like the man and wife who tell the weather: we can't have both at once.

"We may think it extraordinary that the human intellect is able to invent the infinitely subtle mathematical fabric of quantum mechanics, and adapt it to the nature of the things of that alien world which can never be objectified. But the experiment was attended by unprecedented success. It was Eddington who said: 'Formerly we believed that an engineer had created the world. Now we are coming rather to the conclusion that it was a mathematician.' Hence the new, firmly founded trust in mathematics. Hence Dirac's claim: If my theory requires 'negative energy' by reason of its mathematical structure, there must be such a thing, whether or not I can form an intelligible conception of it.

"Bohr and Heisenberg, who have given much thought to the elements of quantum mechanics, define the position as follows: In investigating atomic structure we must make a section—a cut between the object of investigation (the atom) and the investigator himself. The investigator, his apparatus, and the questions which he asks, must be treated as objectifiable in space and time, in accordance with the classic physics. But the atom, the object of research, can be grasped only as a non-objectifiable entity, by quantum mechanics, as a form of mathematical wave-functions, in a mathematical space. Both worlds operate in strict causality, in accordance with cause and effect. The classic physics of the observer, in any case, but

also the products of quantum mechanics, are always to be treated as causal. Uncertainties arise only from the synthesis of two essentially different things, from the existence of the severance: only statistical connections exist between the two worlds. We have seen how observation always means a distortion—an uncontrollable distortion! But nevertheless the juncture is effected with almost prodigious smoothness.

"Perhaps we can go still further, and venture the prediction that for the still smaller region of the atomic *nucleus* yet another novel mode of thought must be necessary—differing from quantum mechanics, which is valid for the atom as a whole. Many things point this way. . . .

"The layman thinks too objectively—it is for this reason that he finds it so difficult to understand modern physics. But until the present century all the physicists had thought thus objectively, and only recently have our eyes been opened and our minds liberated from the fetters of superannuated modes of thought. Physics has had to take up an absolutely different standpoint. It seems that our human contribution to the perception of Nature cannot be evaded; that we shall possibly never know Nature herself—that which lies at the root of everything—but only our perception, our image of Nature; that the smears upon our spectacles are unavoidable.

"Every attempt to penetrate into the interior of an atom and dissect its mechanism destroys the thing we wished to investigate: the functioning of the mechanism—just as every attempt to track down the mystery of life by dissecting the individual parts of a living creature, down to its very atoms, destroys life itself. Niels Bohr has given expression to the idea that something more is concealed behind this external analogy: 'In every experiment on living organisms a certain uncertainty must remain—an uncertainty in respect of the physical conditions to which the organism is subject. And we are forced to conclude that the minimum of freedom which we are obliged, in this respect, to grant the organisms, is quite great enough: It enables them, in some degree, to conceal their ultimate secrets from us. From this point of view the existence of life must be conceived as an elementary fact for which no more definite reason can be given. It must be accepted as the starting-point of biology; much as in the realm of the material

we accept Planck's constant *h*—which appears, from the standpoint of the classic mechanical physics, to be an irrational element, unsusceptible of proof—but which, together with the existence of the smallest particles, such as electrons, protons, forms the basis of atomic physics.'

"And it seems, finally, as though this similarity extended even to psychic processes. I may have a quite unfounded sense of happiness, of high spirits—an intense, pure emotion. Suddenly I become conscious of the fact: 'You are very pleased about something—*why*?'—and this 'why' ushers in a reversal of my emotion. I pry into the original emotion with the probe of the intellect, the conscious, analytical understanding; perhaps I discover the cause—but during this process the centre of gravity of my consciousness is displaced; I am now a psychologist, a thinker and investigator, and no longer so unreasonably cheerful.—So, in the semi-darkness of a room at twilight, shapes and shadows form before the dreaming eye; a cushion, thrown down at random, and the deep cavity of a cupboard, give rise to mysterious figures; a grimacing, menacing face seems to emerge, or a dim mountain landscape. Suddenly my attention is directed to the fact; I fix my eyes upon the strange form, and it melts away—light and shadow in the creases of a cushion—nothing more. In this peculiar parallel of matter, life and intellect, we ought perhaps to see something more than chance. For centuries the world was regarded as a great piece of clockwork, the mechanical plaything of a god. The image proved to be inadequate—and had to be discarded. The small, rigid, lifeless pellets, tossed hither and thither by inexorable mechanical laws, have disappeared. The heavy substance of the matter of which they were formed and in which they remained imprisoned has gradually evaporated. Electrical fields, oscillating tensions, have filled space and banished the mechanical models. And this image, too, is melting in the light of the new knowledge. Only mathematical symbols, the creation of the intellect, are left."

The physicist said no more; he looked at me reflectively. The laboratory, with its gleaming glass tubes, the faint, monotonous humming of the pumps, and the sharp, angry crackling of electrical discharges seemed suddenly an uncanny place. I left the room.

EXPLANATION OF THE PLATES

PLATE 1

SPIRAL NEBULA NGC 3031 IN THE GREAT BEAR

Distance about 3 million light-years. Photographed with the 2½-metre reflector in the Mt. Wilson Observatory, California.—Every one of these nebulae is a distant galaxy or Milky Way, a cluster of many thousands of millions of stars. (Page 224.)

PLATE 2

DISPLACEMENT TOWARDS THE RED

Spectrophotographs of four nebulae taken with the 2½-metre reflector.

The horizontal "Zeppelins" are the nebular spectra; the dark vertical lines above and beneath them are helium lines, which are photographed on the same plate for purposes of comparison. The object of these observations will be seen in the two gaps at the left-hand end of each spectrum. These are the "absorption-lines" of calcium, H and K, which are displaced with increasing velocity towards the right—towards red. (Page 224.)

(*a*) Sky (daylight), normal position of H and K.

(*b*) NGC 221. A photograph: this comparatively near nebula seems to be approaching us; the lines are shifted towards the left. Velocity 185 km./sec.

(*c*) NGC 385; Velocity 4,900 km./sec.

(*d*) NGC 4884; Velocity, 6,700 km./sec.

(*e*) Brightest nebula in Leo; Velocity 19,700 km./sec.

PLATE 3

1. PRISM-SPECTROGRAPH OF INCANDESCENT IRON VAPOUR

Left red, right violet. The black horizontal streak near the bottom is due to a particle of dust in the slit. An apparatus of medium power, which nevertheless distinctly divides the two yellow lines of the Sodium spectrum (D_1 and D_2), with a difference in wave-length of 6/100,000,000 cm. (Pages 233, 251.)

2. SUPERFINE STRUCTURE OF THE SODIUM LINES (INTERFEROMETER EXPOSURE)

The interference rings are here due to multiple reflections from two parallel silvered glass plates (Perot–Fabry Interferometer). The influence of the atomic nucleus is plainly visible: Each of the two

D-lines appears to be duplicated; the two dark inner circles are the two "components" of D_2, the two next, those of D_1; the faint innermost circle is due to argon. Towards the circumference this formation is repeated; but the separate components of D_2, plainly divided on the negative, show in the reproduction as one thick line. The difference in the wave-lengths of the components of D_2 is 2/10,000,000,000 cm.; the distance between D_1 and D_2 would be, on the same scale, about 30 cm.; that they are here seen close together is explained by the peculiarities of the interferometer. (Page 251).

3. A 5-METRE SPECULUM FOR THE MT. WILSON OBSERVATORY

The 5-metre speculum should reveal spiral nebulae as yet invisible. Despite all care, the glass disk appears to have been cast unsuccessfully; it is said that fragments of slag came away from the mould. If so, years of work have been wasted. (Page 220.)

PLATE 4

ELECTRON WAVES

1. The black specks (the Laue diagram) occur when a single well-formed crystal is irradiated. The electron-picture was produced by a mica crystal. The result corresponds with that of the Davisson experiment. (Pages 166, 278.)

2. On the irradiation of a sheet of metallic foil, which does not consist of a single crystal, but of many small "crystallites," these diffraction-rings are seen (Debye–Scherrer method).

By this method Prof. G. P. Thomson obtained the first photographic evidence of electron-waves; Davisson and Germer employed slightly different method of demonstrating diffraction. (Pages 166, 278.)

PLATE 5

PROGRESSIVE DEMOLITION OF INCANDESCENT CATHODE

A photograph which could have been secured only with the Electron-microscope. It shows the changes in an overheated cathode; the lines are scratched in the metal. The electrons are emitted from the bright spots. It will be seen that as the destruction continues they collect more and more in the scratches. (Page 280.)

PLATE 6

LABORATORY FOR THE DISINTEGRATION OF THE ATOM; COCKCROFT AND WALTON, CAMBRIDGE

The glass cylinder on the right is the actual discharging-tube, in which protons are driven through fields of 100,000 to 600,000 volts. They shoot downwards out of the tube with great velocity, and

bombard the target (inside the cloth-covered box). In the background is the spark-gap for measuring the tension; the higher the tension, the greater the distance between the balls which can still be leapt by a powerful spark. In the extreme background is J. D. Cockcroft. (Page 298.)

PLATE 7

DISINTEGRATION OF THE ATOM

1. Disintegration of nitrogen by alpha particles; the first photographic evidence of atomic disintegration. (Centre) An alpha-particle has penetrated the nitrogen nucleus; a hydrogen nucleus is expelled with great energy, tracing the thin trail running diagonally downwards towards the right. The path of the residual nucleus can be followed a little farther. The forks and bends at the ends of other trails signify harmless collisions. (Page 296.)

2. Dee, in Cambridge, succeeded in introducing the hail of projectiles of the Cockcroft apparatus directly into the cloud-chamber. Heavy hydrogen, when bombarded with heavy hydrogen, breaks up into light hydrogen (H^1), and a new, still heavier hydrogen (H^3 or T^3), which are hurled away in opposite directions. The single trail *n* near the top was caused by the collision of a neutron with an atom of gas. Such photographs have been obtained also by Kirchner in Munich.

PLATE 8

NEWCOMERS

Neutron.—Alpha-rays—the "fan" at the bottom of the picture—have liberated neutrons from a film of beryllium (the white diagonal line at the bottom), which pass invisibly through the chamber. Two of them have shot a hydrogen-ray out of the paraffin cylinder in the middle. We see that not a single alpha-ray has reached it; so that no alpha-ray can be held responsible for this process of liberation. (Page 307.)

Positron.—An unusually fine photograph of a positive and a negative electron from a lead target. The energy of each particle, about 0·5 million volts. The direction of the magnetic field is vertical to the plane of the picture. The process of liberation is rather complicated: Calcium fluoride is bombarded with polonium α-rays outside the chamber. The neutrons thereby released apparently liberate a γ-ray in the lead, which gives rise to the two electrons. (Page 310.)

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